Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

EM Sensing & Treatment of Living Things: Using Microwaves to Detect & Treat Disease in Humans & Trees

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Northeastern University, Boston, MA

IEEE Distinguished Lecture, UCF, January 26, 2018

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Abstract

Because of their ability to penetrate and heat, electromagnetic waves have found use in several unusual applications, specifically in interaction with biological tissue. Microwave radar has been used as an anatomic imaging modality for detecting breast cancer, and THz radiation is being proposed for vulnerable plaque identification. Using a simple conformal antenna, microwave sensing of trees can alert arborists if there is an otherwise undetectable infestation of Asian Long-Horned beetle. By depositing microwave power at depth, cancerous or otherwise diseased tissue can be non-invasively heated and inactivated or ablated while sparing healthy surrounding tissue. This survey presentation will touch on a variety of life science electromagnetic applications, discussing feasibility, advantages, efficacy, and limitations of the proposed approaches.

Biography

Carey M. Rappaport (IEEE M, SM 96, F 06) received five degrees from the Massachusetts Institute of Technology: the SB in Mathematics, the SB, SM, and EE in Electrical Engineering in June 1982, and the PhD in Electrical Engineering in June 1987. He is married to Ann W. Morgenthaler, and has two children, Sarah and Brian.

Prof. Rappaport has worked as a teaching and research assistant at MIT from 1981 until 1987, and during the summers at COMSAT Labs in Clarksburg, MD, and The Aerospace Corp. in El Segundo, CA. He joined the faculty at Northeastern University in Boston, MA in 1987. He has been Professor of Electrical and Computer Engineering since July 2000. In 2011, he was appointed College of Engineering Distinguished Professor. During fall 1995, he was Visiting Professor of Electrical Engineering at the Electromagnetics Institute of the Technical University of Denmark, Lyngby, as part of the W. Fulbright International Scholar Program. During the second half of 2005, he was a visiting research scientist at the Commonwealth Scientific Industrial and Research Organisation (CSIRO) in Epping Australia. He has consulted for CACI, Alion Science and Technology, Inc., Geo-Centers, Inc., PPG, Inc., and several municipalities on wave propagation and modeling, and microwave heating and safety. He was Principal Investigator of an ARO-sponsored Multidisciplinary University Research Initiative on Humanitarian Demining, Co-Principal Investigator of the NSF-sponsored Engineering Research Center for Subsurface Sensing and Imaging Systems (CenSSIS), and Co-Principal Investigator and Deputy Director of the DHS-sponsored Awareness and Localization of Explosive Related Threats (ALERT) Center of Excellence.

Prof. Rappaport has authored over 430 technical journal and conference papers in the areas of microwave antenna design, electromagnetic wave propagation and scattering computation, and bioelectromagnetics, and has received two reflector antenna patents, two biomedical device patents and four subsurface sensing device patents. He was awarded the IEEE Antenna and Propagation Society's H.A. Wheeler Award for best applications paper, as a student in 1986. He is a member of Sigma Xi and Eta Kappa Nu professional honorary societies.

Outline

- Why probe with microwaves?
- Breast cancer imaging
- Mm-wave vulnerable plaque detection
- Thermal treatment with microwaves
- Microwave cardiac ablation
- Microwave detection of insect infestation in trees

Microwaves as Probes to Detect Subsurface Features -- Radar

Microwave radar

- Transmit wideband pulse into medium, observe reflection from internal dielectric constant inhomogeneity
- Relative amplitude and delay of return gives size and distance to subsurface objects
- Multiple observations needed to triangulate cross-range position
- Best for small number of isolated targets

Microwaves as Probes to Detect Subsurface Features -- Tomography

Microwave tomography

- Transmit and receive from various positions, measure phase and amplitude
- Reconstruct internal dielectric structure
- Number of Tx/Rx ~ number of pixels in image
- Best for determining material distribution
- Works poorly for big and for high contrast objects

Microwave Hyperthermia and Ablation

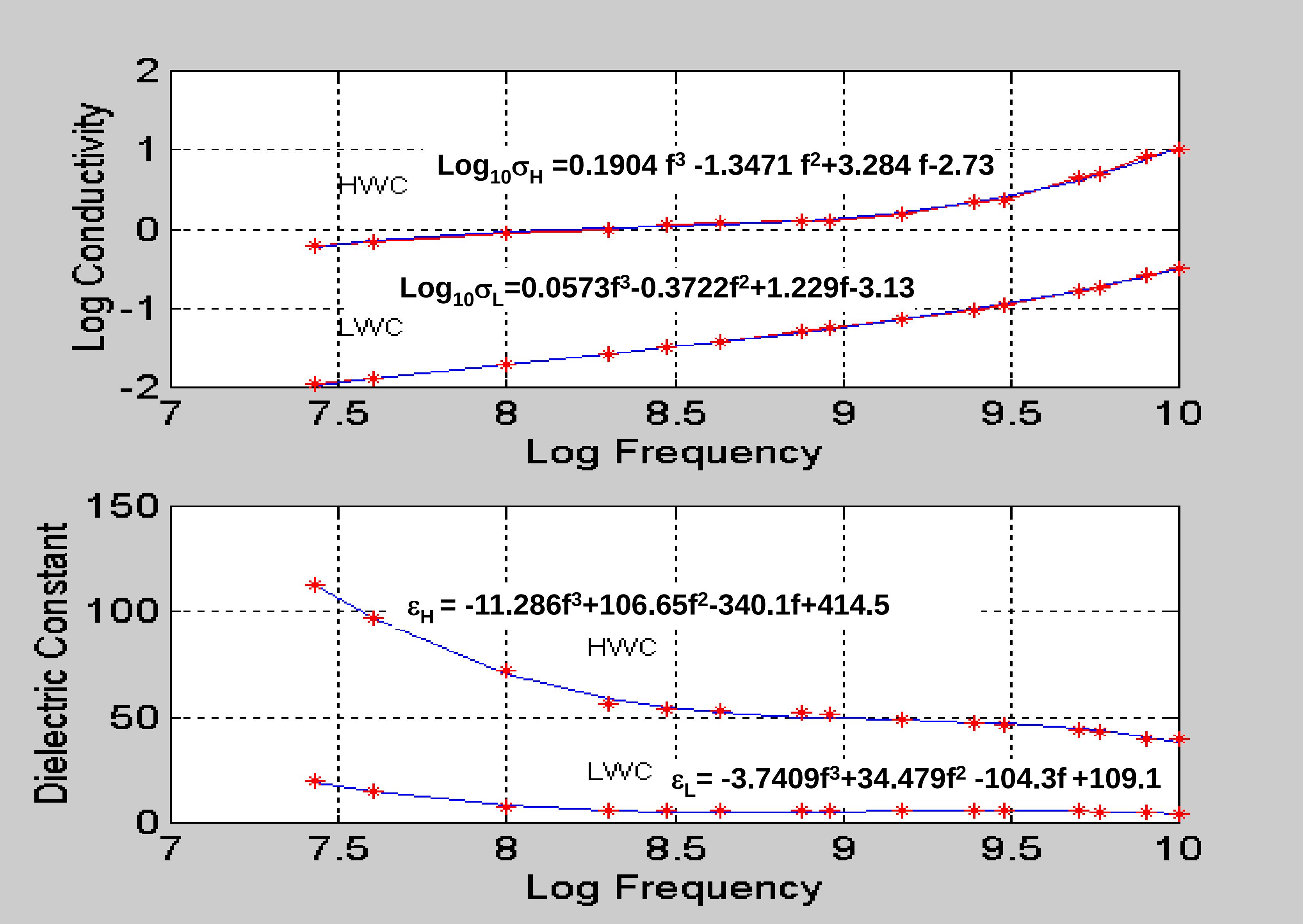
- Use dissipated microwave power to heat tissue
- Focus to heat specific regions
  - Internally, for non-invasive treatment
  - Throughout tissue volume for uniform ablation
- Heat from both sides or multiple directions for maximum constructive effect
- Control nulls to spare healthy tissue

Dielectric Contrast is the only Relevant Detection Parameter in Microwave Imaging

- Low water content (LWC) tissue (fat, bone) has small dielectric constant
- High water content (HWC) tissue (muscle, organ, blood, fibrous) has large dielectric constant

- Tumor is HWC, “Breast tissue is LWC”, so target object has high contrast relative to background – easy to distinguish

Measured and Modeled Conductivity and Dielectric Constant for HWC and LWC Tissue

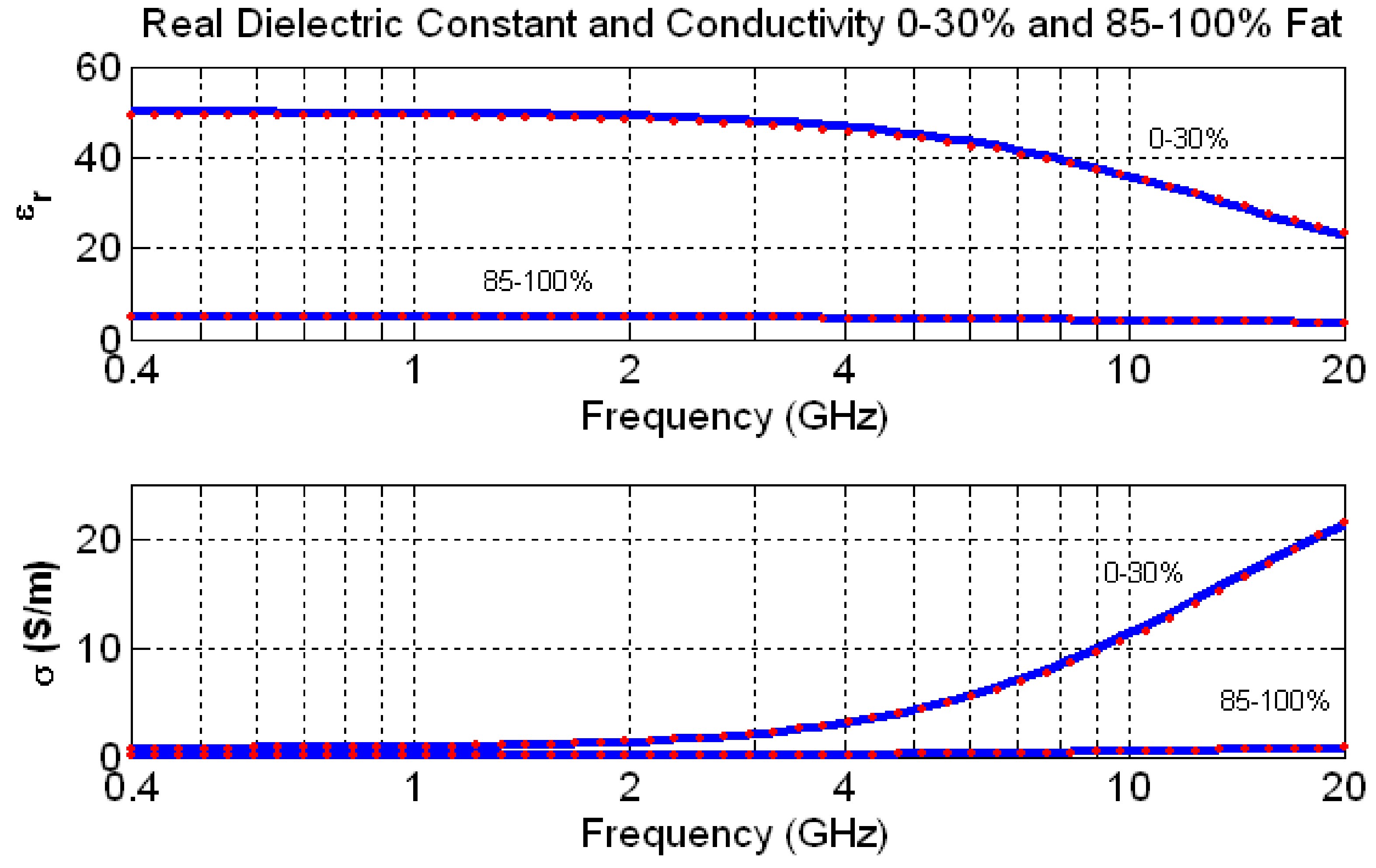


MICROWAVE RADAR DETECTION OF BREAST CANCER

Challenges with Breast Cancer Microwave Detection

- Tumor Dielectric constant is close to that of Fibroglandular tissue (~10%)
- Fibroglandular tissue is randomly and non-uniformly distributed
  - Background is irregular – hard to generalize
  - Tumor is low contrast scatterer – hard to isolate
- Wave propagation is dispersive in fibroglandular tissue
  - Behavior depends on frequency
  - Pulse shape changes with distance
- Penetration decreases rapidly increasing freq.
- Coupling to lossy tissue across wide bandwidth requires special bolus material

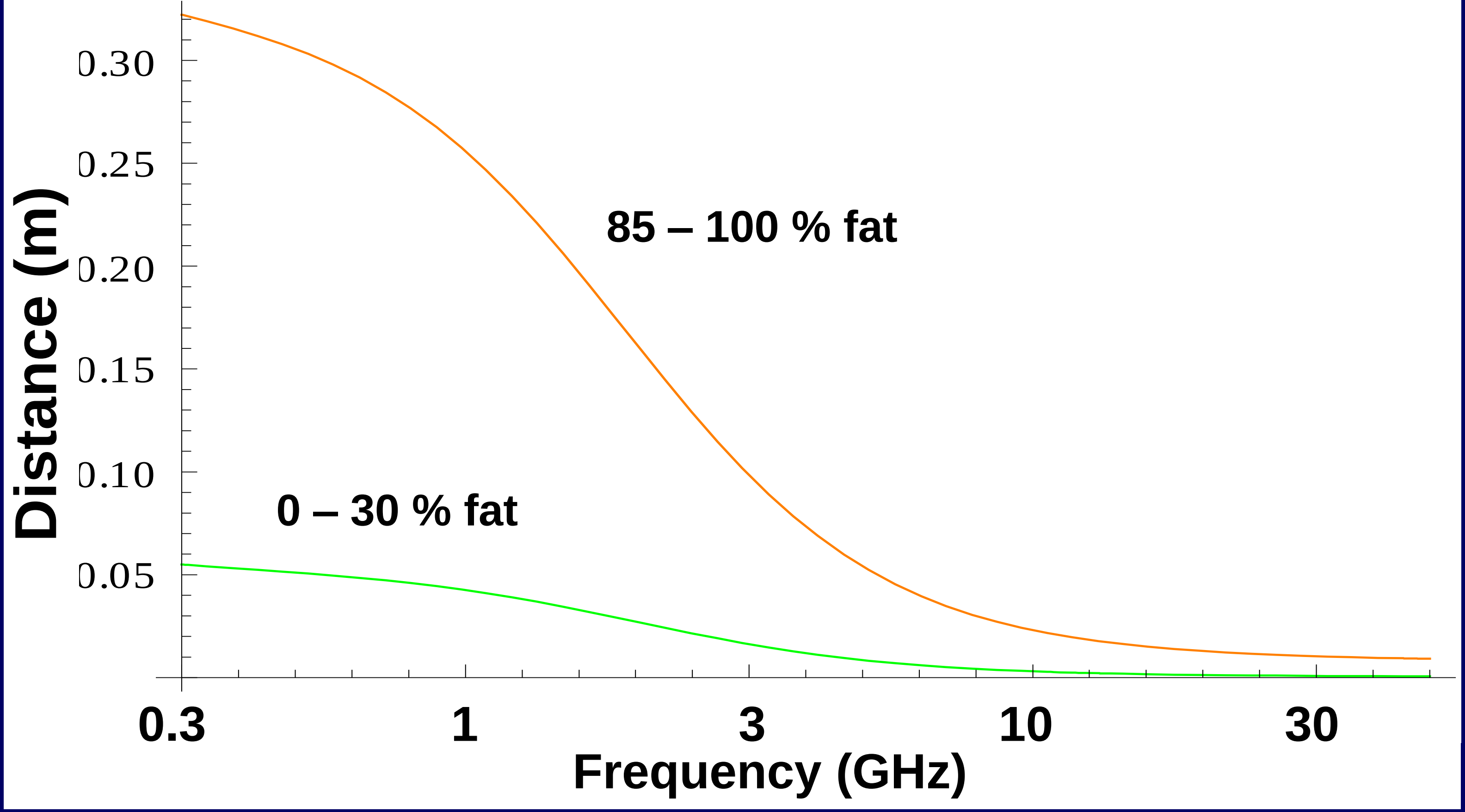
Unfortunately, Only Breast Adipose Tissue is LWC



Lazebnik, M., Watkins, C., Hagness, S., Booske, J., McCartney, L., Popovic, D., Okoniewski, M., Lindstrom, M., Harter, J.,Sewall, S., Magliocco, A., "Dielectric Spectroscopy of Breast Reduction Tissue Specimens at Microwave Frequencies: Conclusions from a Large-Scale Multi-Institutional Study," *IEEE Int'l Sym. Ant. Prop.*, pp. 394, July, 2006.

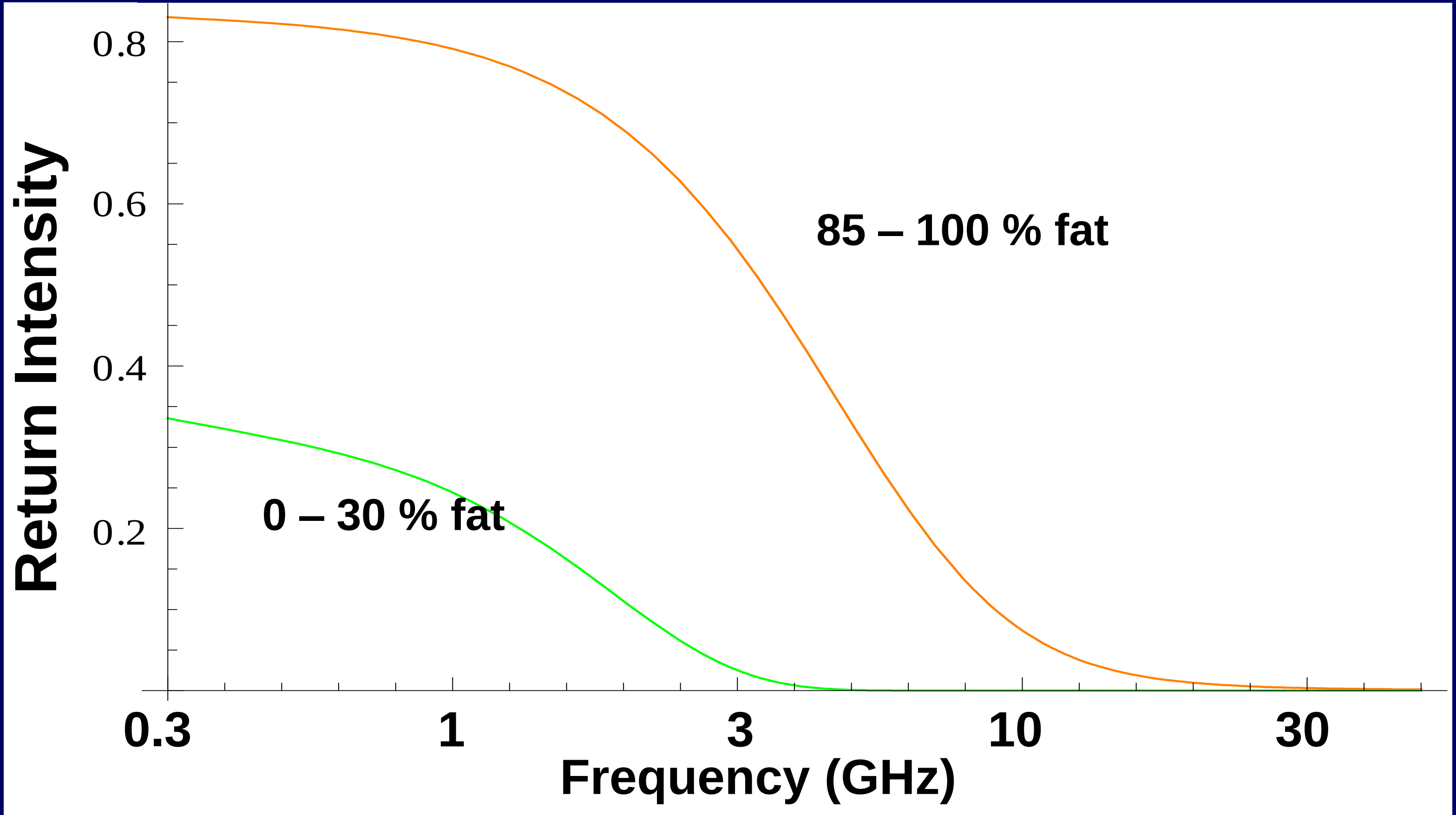
Penetration Decreases Rapidly with Increasing Frequency

Distance for 1/e Attenuation in Adipose and Fibroglandular Breast Tissue

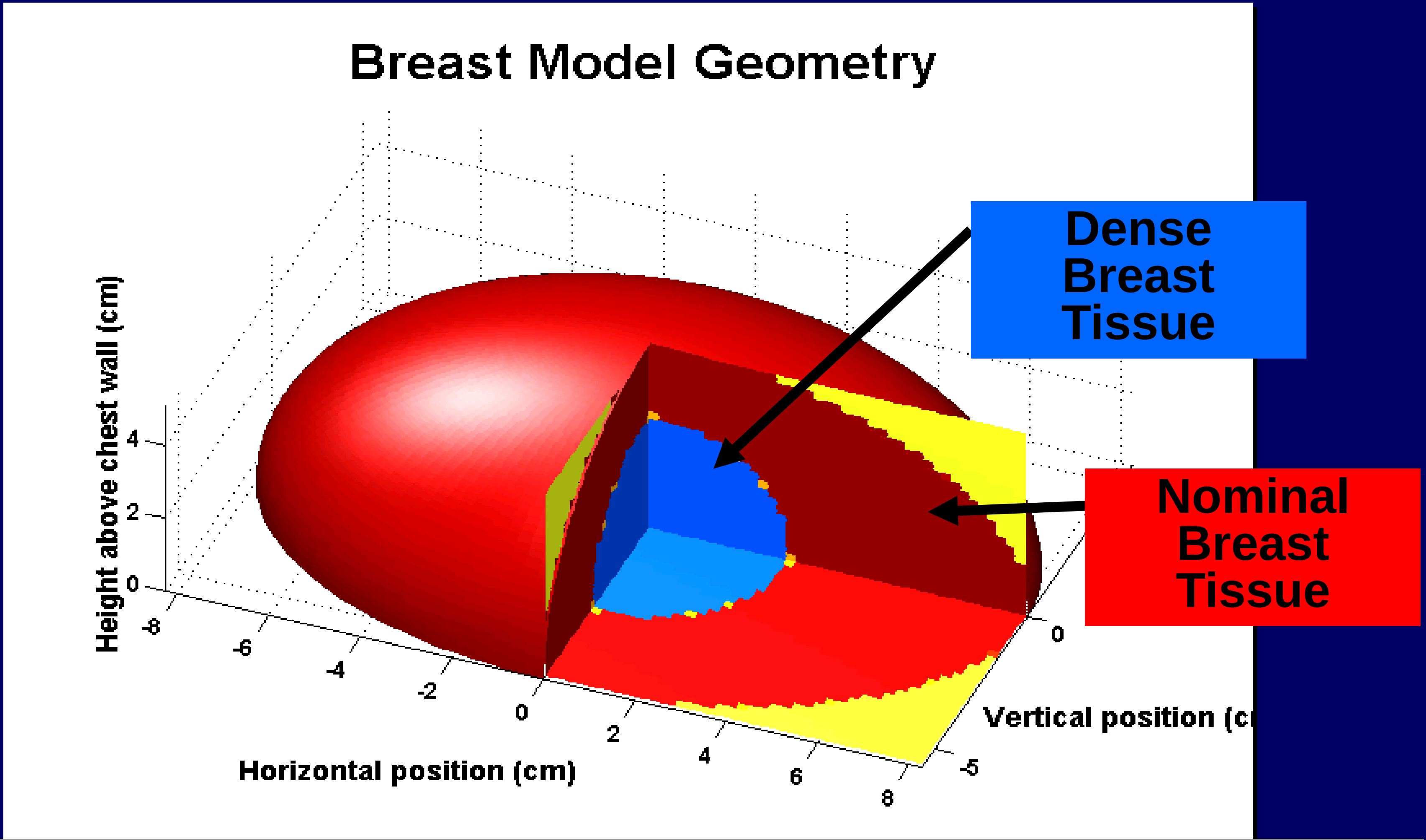


Signal Strength Decreases Rapidly with Increasing Frequency

Relative Signal Strength from Perfect Reflector at 3cm depth in Adipose and Fibroglandular Tissue

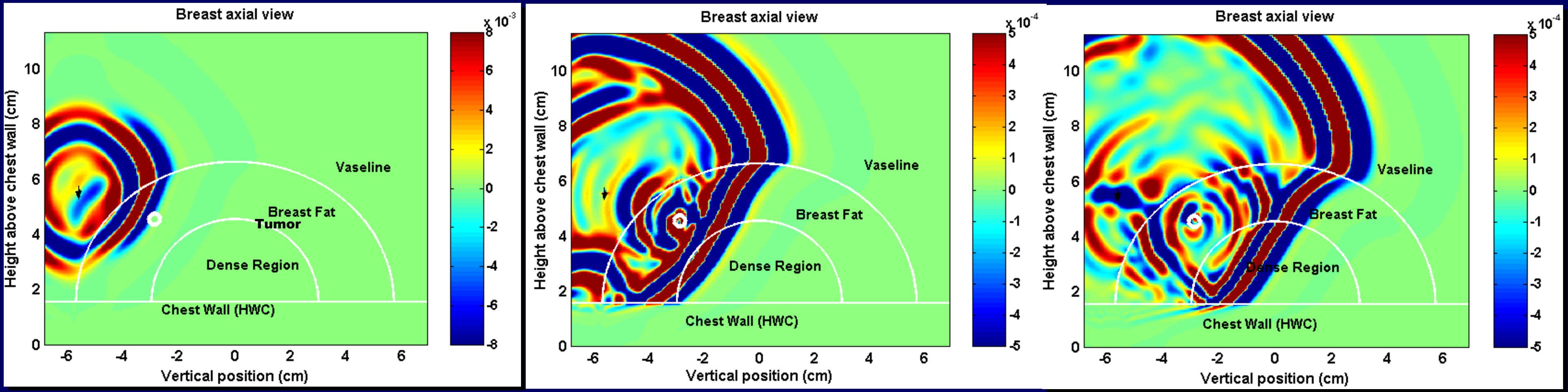


3D Time Domain Microwave Scattering in Realistic Biological Tissue Model S


Breast Model Geometry
Dense Breast Tissue
Nominal Breast Tissue
Height above chest wall (cm)
4
2
0
-8
-6
-4
-2
0
2
4
6
8
Horizontal position (cm)
0
-5
Vertical position (c

4 GHz Modulated Gaussian spherical wave illumination
Tumor modeled as an embedded 3mm High Water content Tissue

Impulse Radar Propagation Modeling of Point Source Interaction with Breast with Tumor

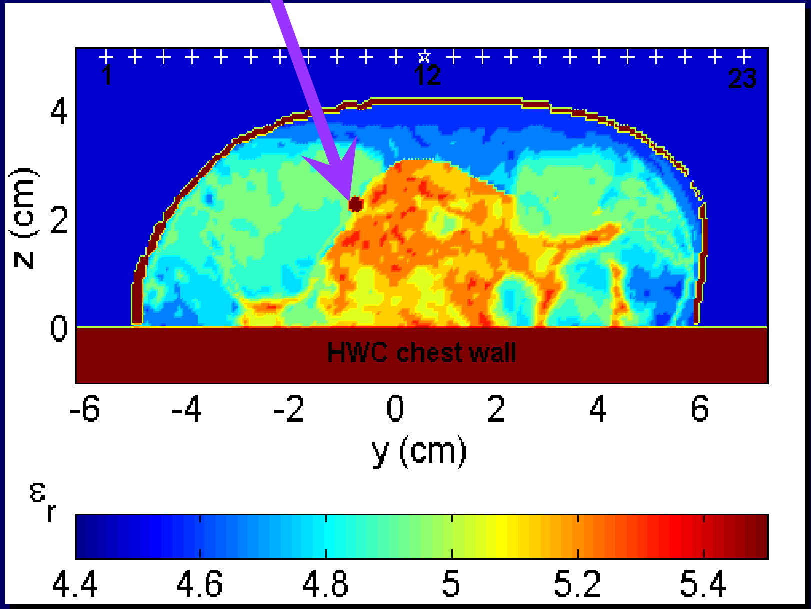


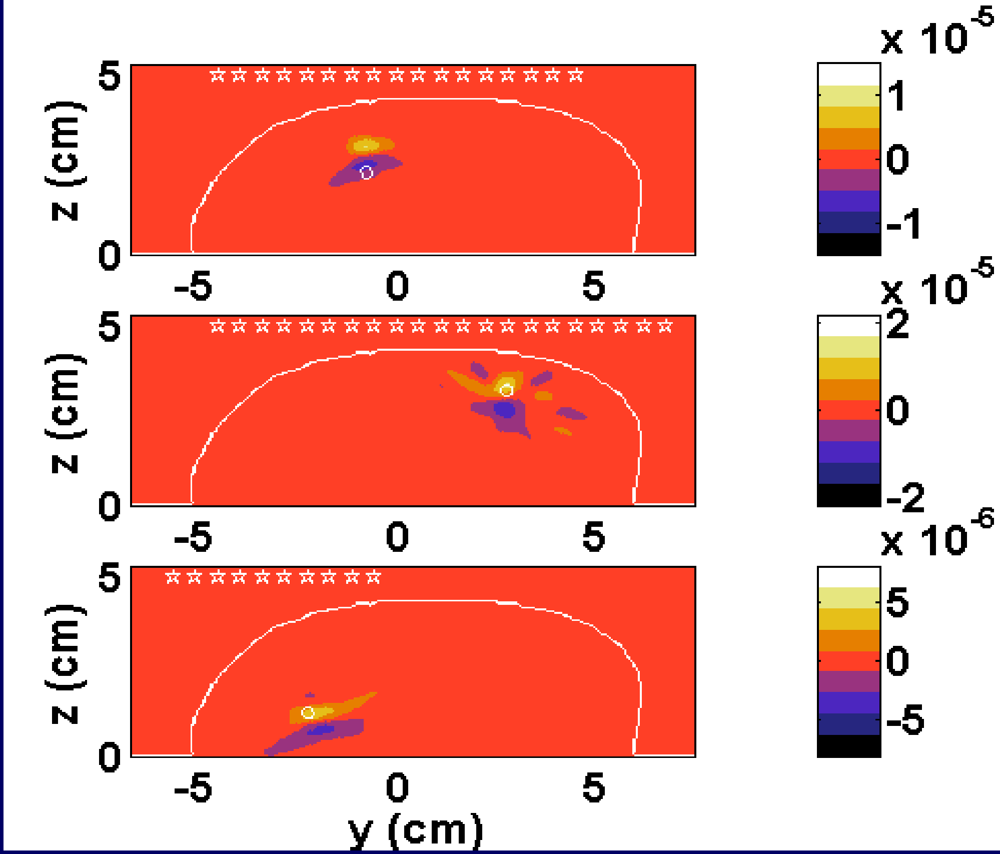
Notes:

- Breast fat, dense breast tissue region and tumor are all non-dispersive
- Non-dispersive constant permittivities and conductivities are those of the dispersive models at the central frequency of 8 GHz.
- Significant difference in the scattered signal, at (-4, 6), from the tumor is observed.

Time Reversal Reconstruction of Small Breast Tumor - Realistic Model

High water content 3mm tumor in MRI-based breast model with extensive fibroglandular tissue





Reconstruction using FDTD for 3 tumor positions without *a priori* knowledge of background

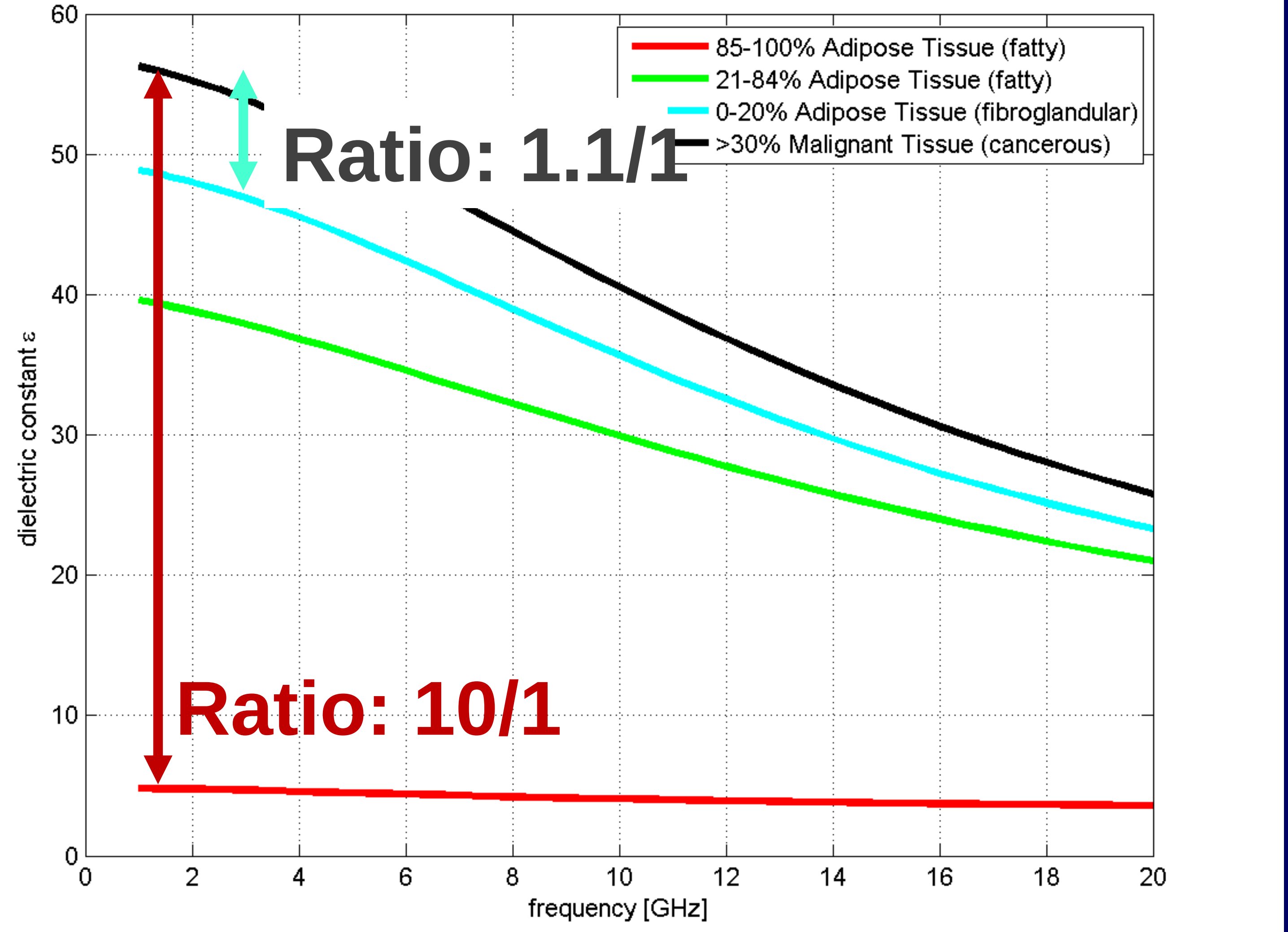
Continuing Subsurface Modeling Challenges

- Accurate 3D models are too slow for efficient inversion applications
  - Nearfield analysis of media with random inhomogeneous & rough interfaces is hard to generalize
  - Exact target shape model is important for characterization, but requires fine sampling

- Obtaining material parameters that correlate with desired sensing aspect is difficult (*in vivo* tissue, deep geological structure)
  - Targets with low contrast
  - Readily changing random variations

2. Existing Imaging Techniques: NRI

Contrast in dielectric constant



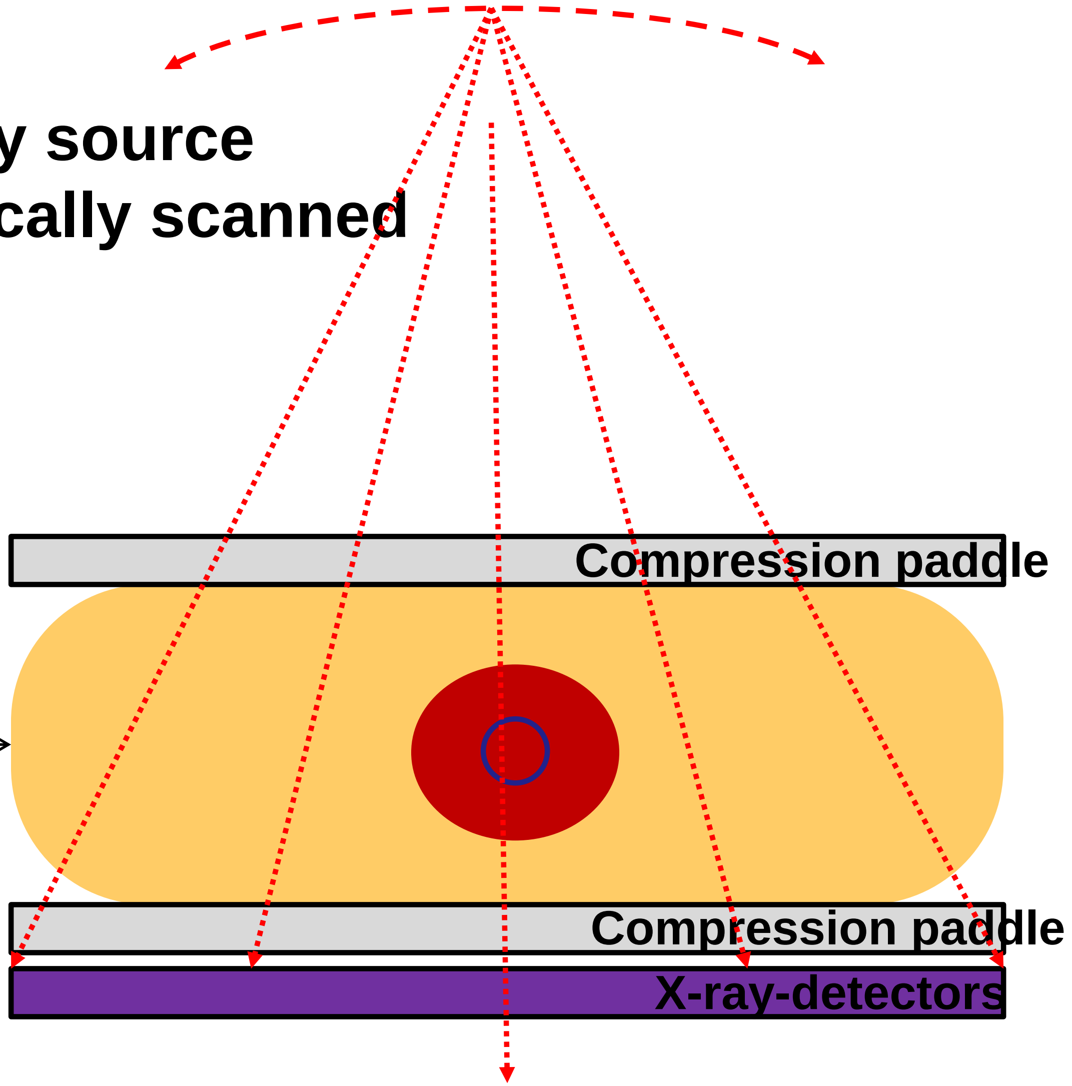
Ratio: 1.1/1

Ratio: 10/1

Hybrid DBT / NRI Technique

- Utilizes the benefits of both imaging techniques
- Collect DBT and NRI measurements simultaneously
- Generate 3D DBT image
- Use DBT reconstruction to model the NRI measurements and enhance NRI reconstruction

3. Hybrid DBT / NRI Technique



X-ray source
mechanically scanned

Compression paddle

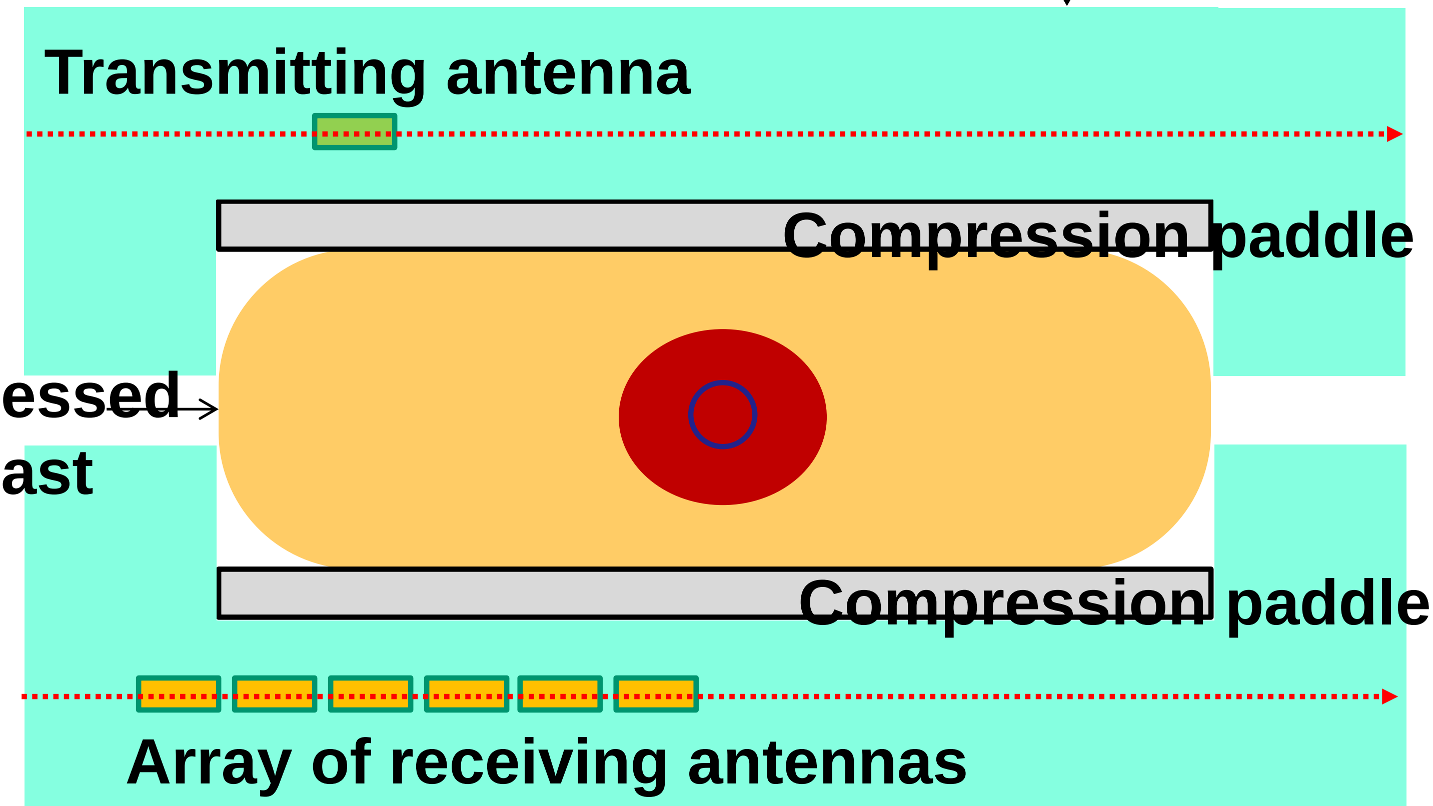
Compressed breast

Compression paddle

X-ray-detectors

Step-1: X-ray-based Digital Breast Tomosynthesis

4. Hybrid DBT / NRI Technique



Plastic container
filled with a bolus matching liquid

Transmitting antenna

Compression paddle

Compressed
breast

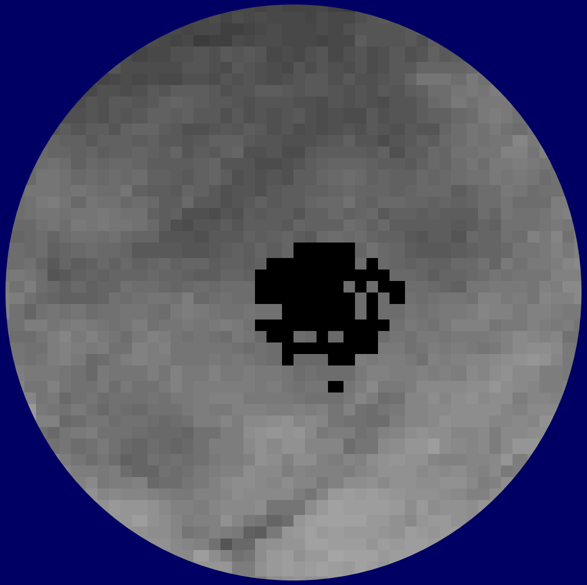
Compression paddle

Array of receiving antennas

Plastic container filled with a bolus matching liquid

Step-2: Near-field Microwave Radar Imaging

GT Image: Diseased Case

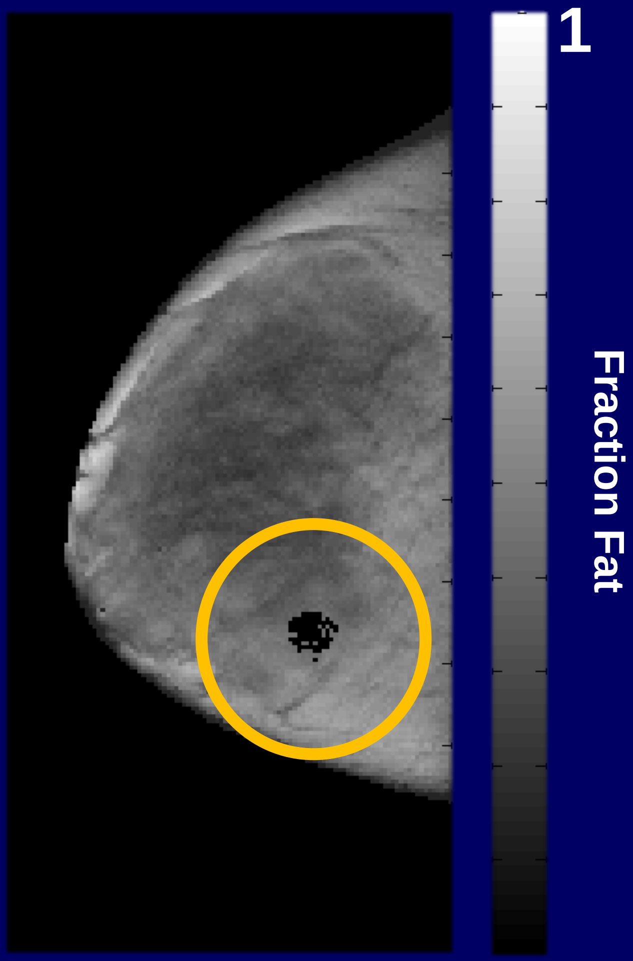


Lesion

12 mm diameter

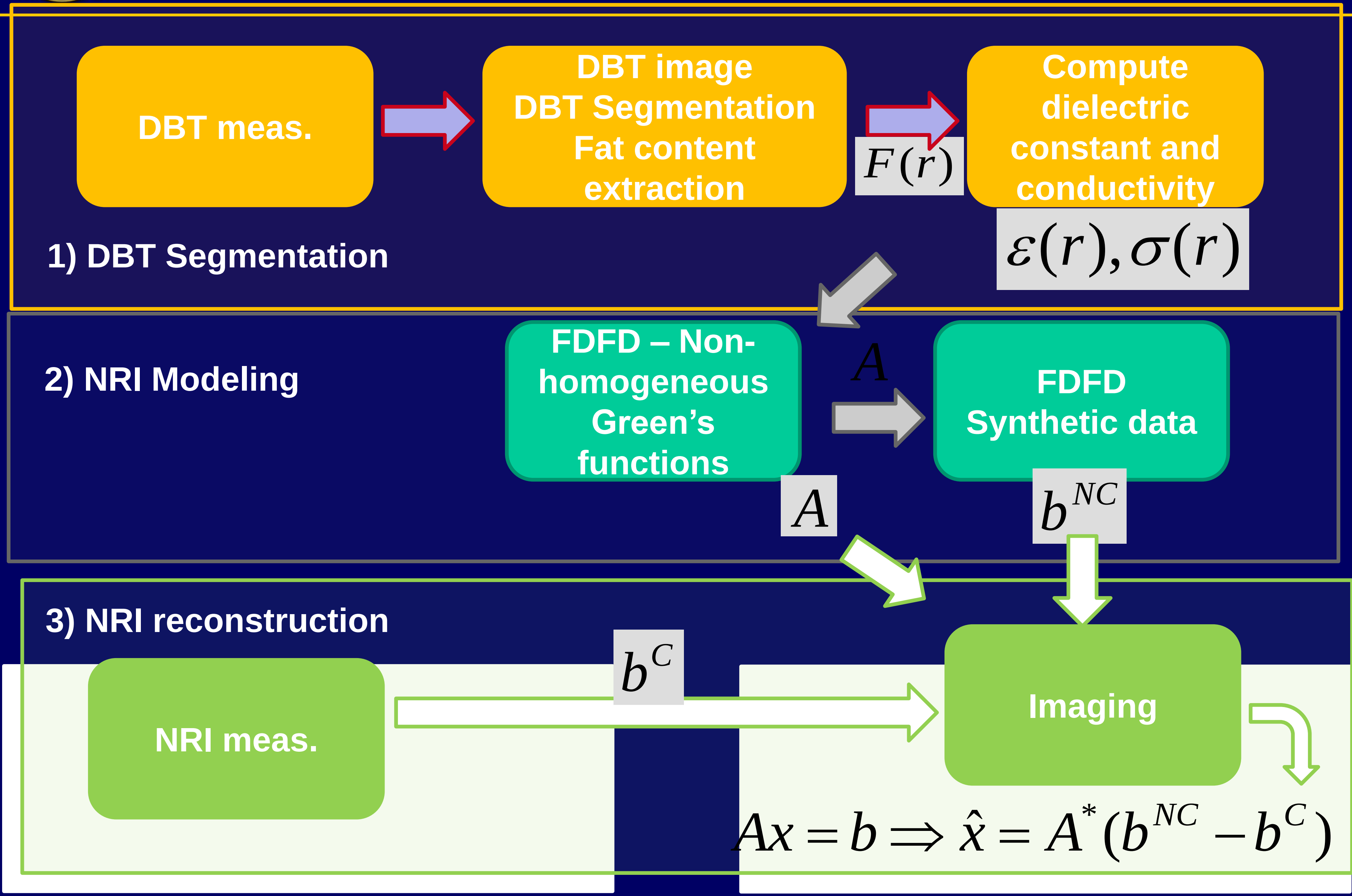
$$\epsilon_R = 56$$

$$\sigma = 1.58$$


1
Fraction Fat

*** Z = 36 cross section shown**

Hybrid DBT / NRI Technique



DBT meas.

DBT image
DBT Segmentation
Fat content extraction

$F(r)$

Compute dielectric constant and conductivity

$\varepsilon(r), \sigma(r)$

1) DBT Segmentation

2) NRI Modeling

FDFD – Non-homogeneous Green's functions

A

FDFD
Synthetic data

A

b^{NC}

3) NRI reconstruction

NRI meas.

b^{C}

Imaging

$$Ax = b \Rightarrow \hat{x} = A^{*}(b^{NC} - b^{C})$$

2. Computational Results: 3D imaging

- **16 antennas: levels relative to**

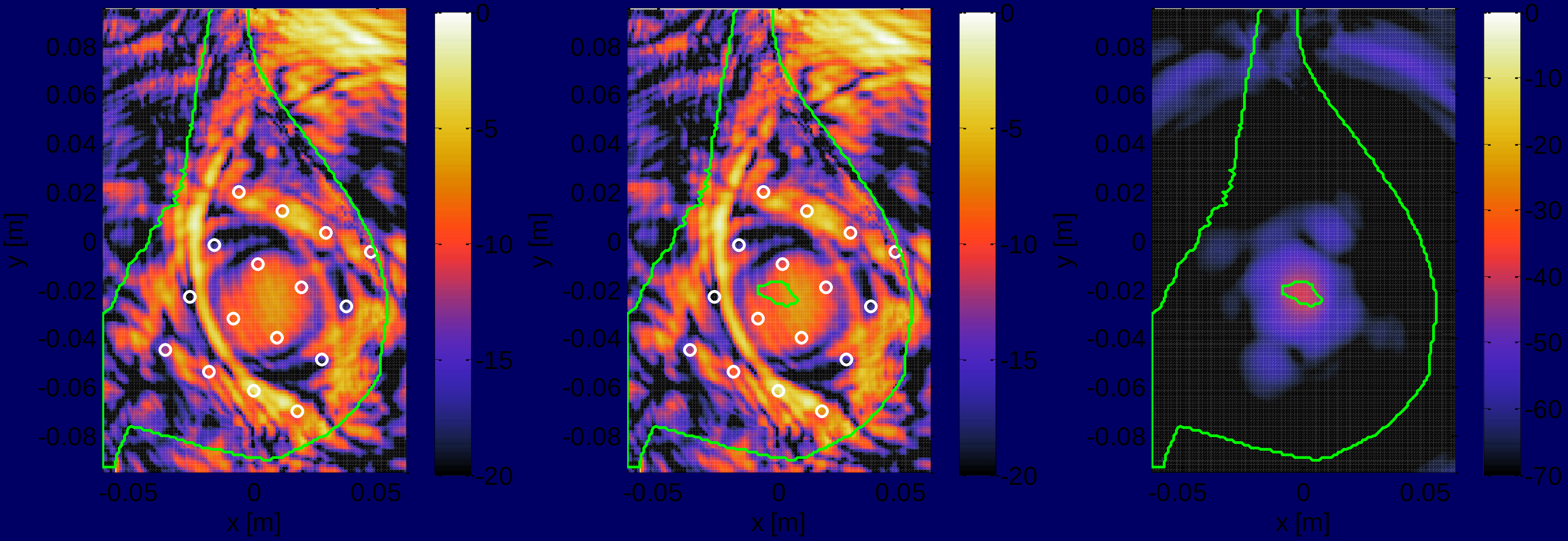
$$I^{NC} = \hat{x}^{NC} = A^{*}b^{NC}$$

$$I^{C} = \hat{x}^{C} = A^{*}b^{C}$$

$|\mathrm{I}^{NC}|$ **(Non-cancerous)**

$|\mathrm{I}^{C}|$ **(Cancerous)**

$|\mathrm{I}^{C} - \mathrm{I}^{NC}|$ **-39dB**



0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
y [m]
-0.05
0
0.05
x [m]
0
-5
-10
-15
-20
0
-10
-20
-30
-40
-50
-60
-70

Computational Results: 3D imaging

- **256 antennas: levels relative to**

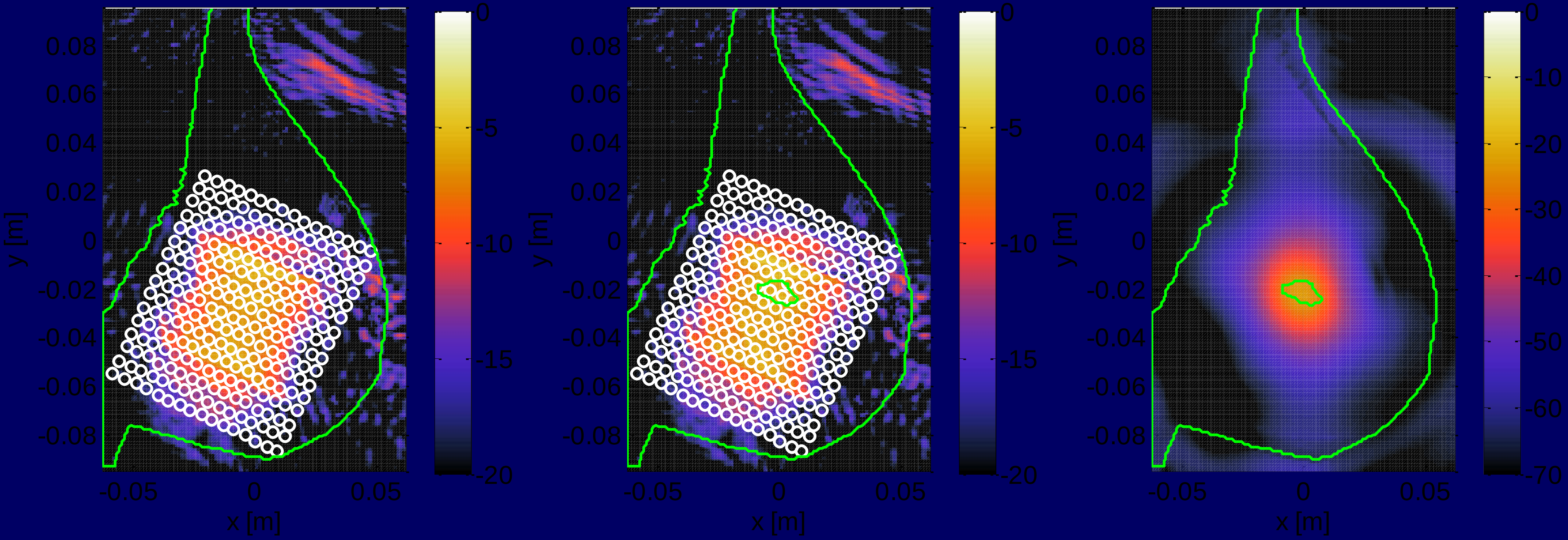
$$I^{NC} = \hat{x}^{NC} = A^{*}b^{NC}$$

$$I^{C} = \hat{x}^{C} = A^{*}b^{C}$$

$|\mathrm{I}^{NC}|$ **(Non-cancerous)**

$|\mathrm{I}^{C}|$ **(Cancerous)**

$|\mathrm{I}^{C} - \mathrm{I}^{NC}|$ **-23dB**



Breast Cancer Imaging Conclusions

- Fusing DBT with NRI improves the performance of the NRI reconstruction
- DBT image segmentation used to derive a 3D map of the spatial distribution of constitutive parameters in the breast
- Computational modelin to derive the numerical Green function
- Cancer successfully imaged when scattering of healthy breast (heterogeneous background) is subtracted

THZ VULNERABLE PLAQUE DETECTION TO PREVENT SUDDEN CARDIAC DEATH

THz Vulnerable Plaque Detection

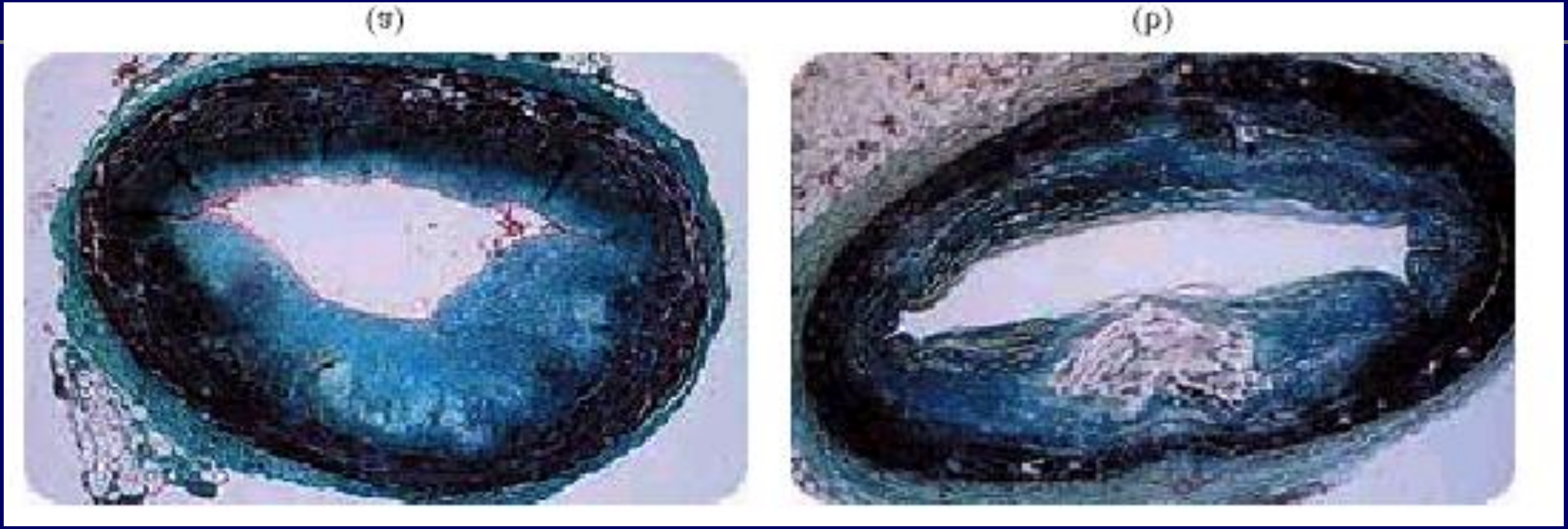
Acute Myocardial Infarction

- Commonly known as heart attack
- Leading cause of death in U.S. and industrialized countries
- Often from the rupture of vulnerable plaques in coronary artery
- Sudden, complete blockage of artery with little warning
- Results in death of the heart muscle

Characteristics of Thin-Cap Fibroatheroma

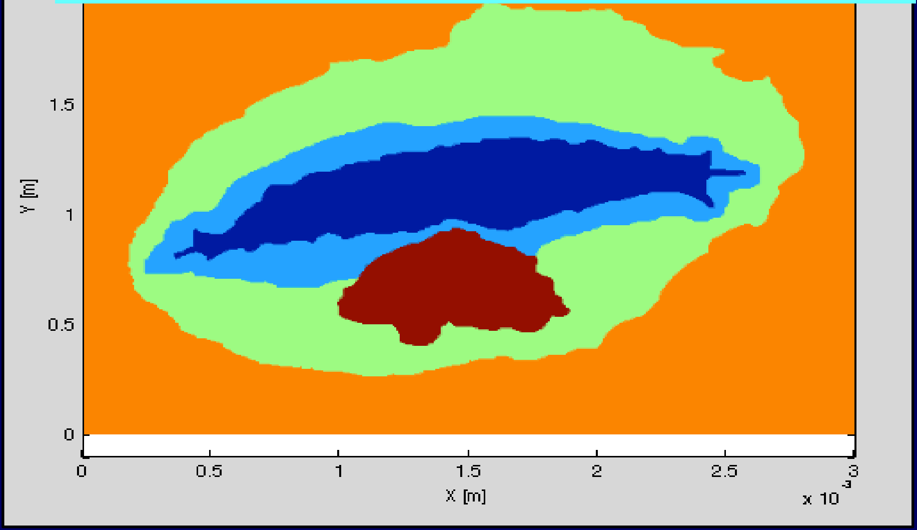
- Form of vulnerable plaque
- Culprit lesion in 8 out of 10 sudden cardiac deaths
- Large core containing a lipid pool & white blood cells
- Thin fibrous cap (<65 microns)
- Conventional imaging approaches fail
- Asymptomatic

Healthy and Vulnerable Plaque Geometry



Healthy, with 50 % reduced lumen

Vulnerable, with large differentiated lipid pool

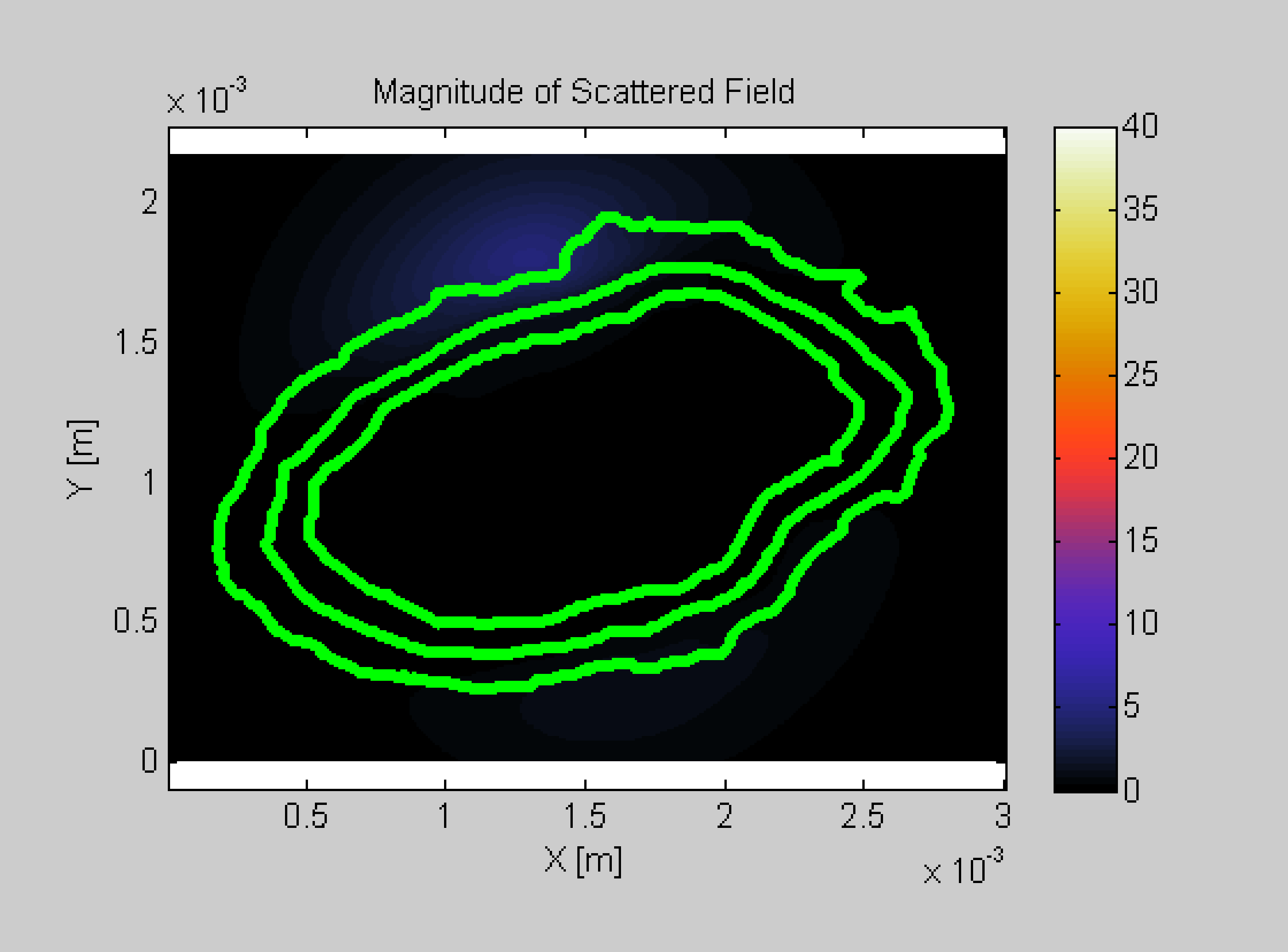

Y [m]
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
X [m]
x 10^{-3}

Images courtesy of CIMIT

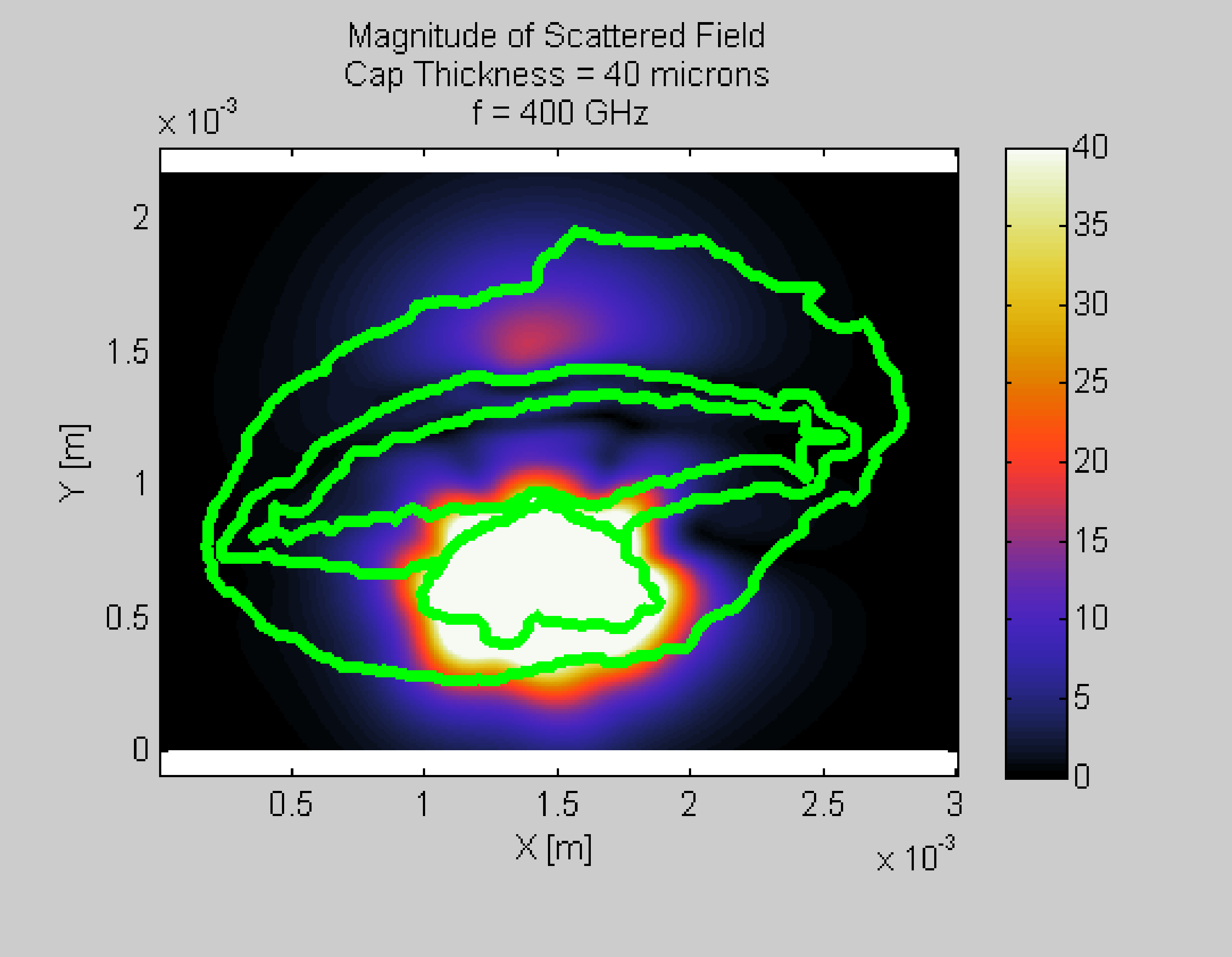
Sensing Approach

- Insert catheter in suspected artery
- Use multi-monostatic field samples from circumference of catheter
- Reposition catheter by pulling back from final probing position
- Remove common background response
- Triangulate on difference field scattered by lipid pool, if any
- Determine position and thickness

Magnitude of Scattered Field Healthy Blood Vessel; 400 GHz



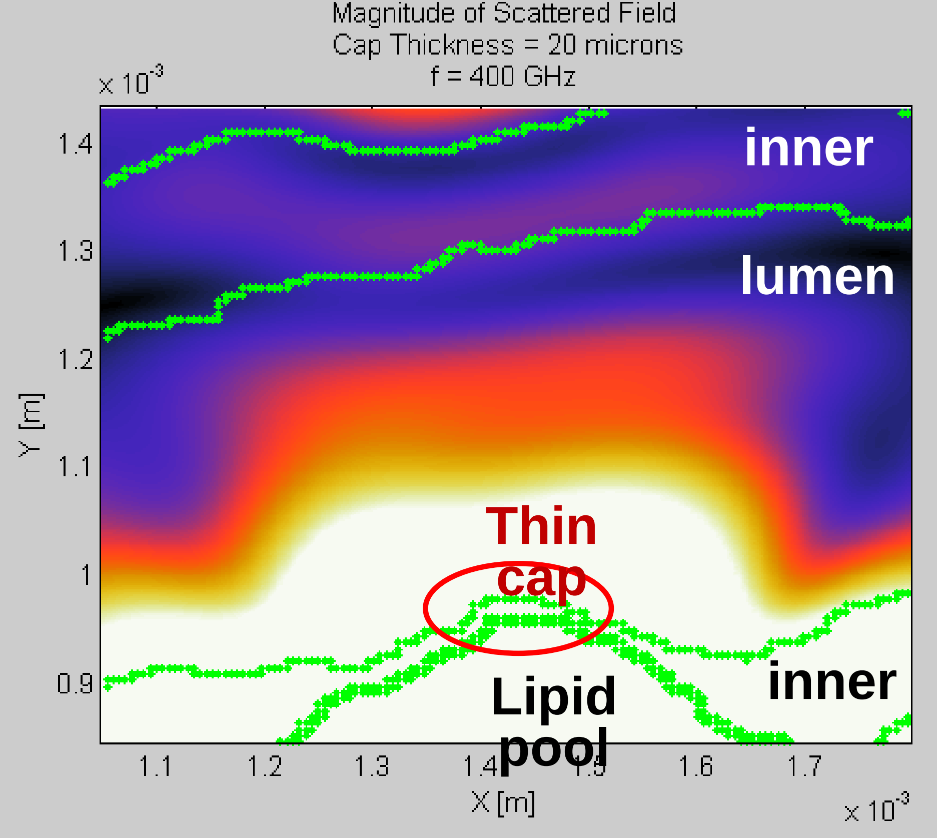
Magnitude of Scattered Field Vulnerable Plaque; 400 GHz

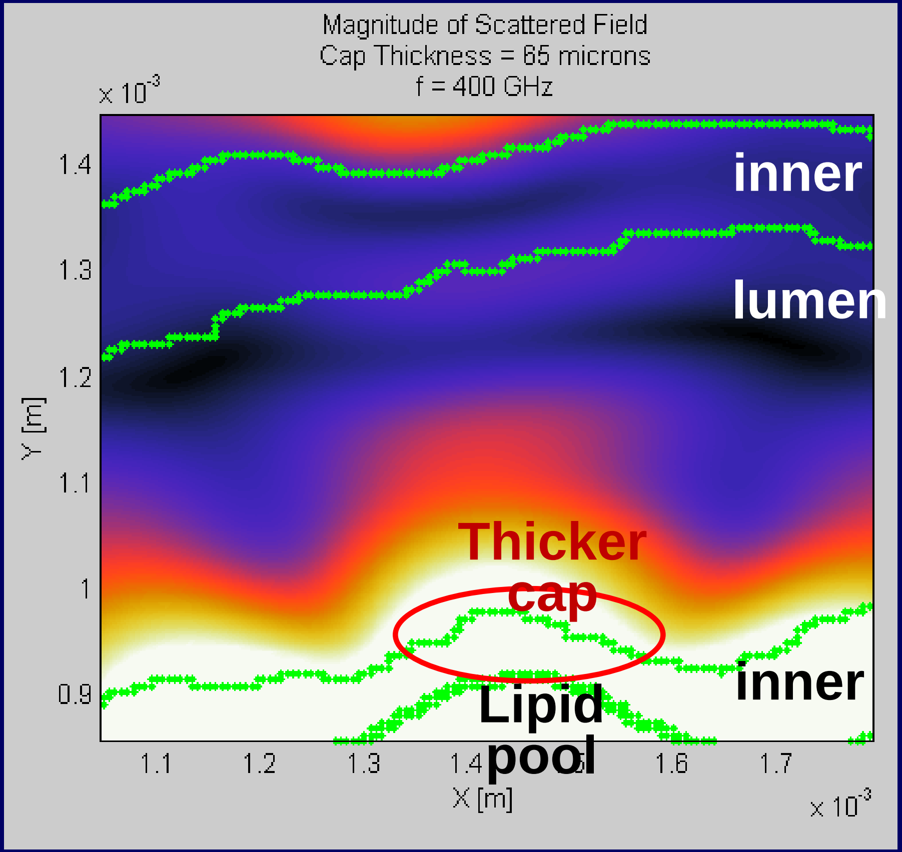


Magnitude of Scattered Field Vulnerable Plaque; 400 GHz

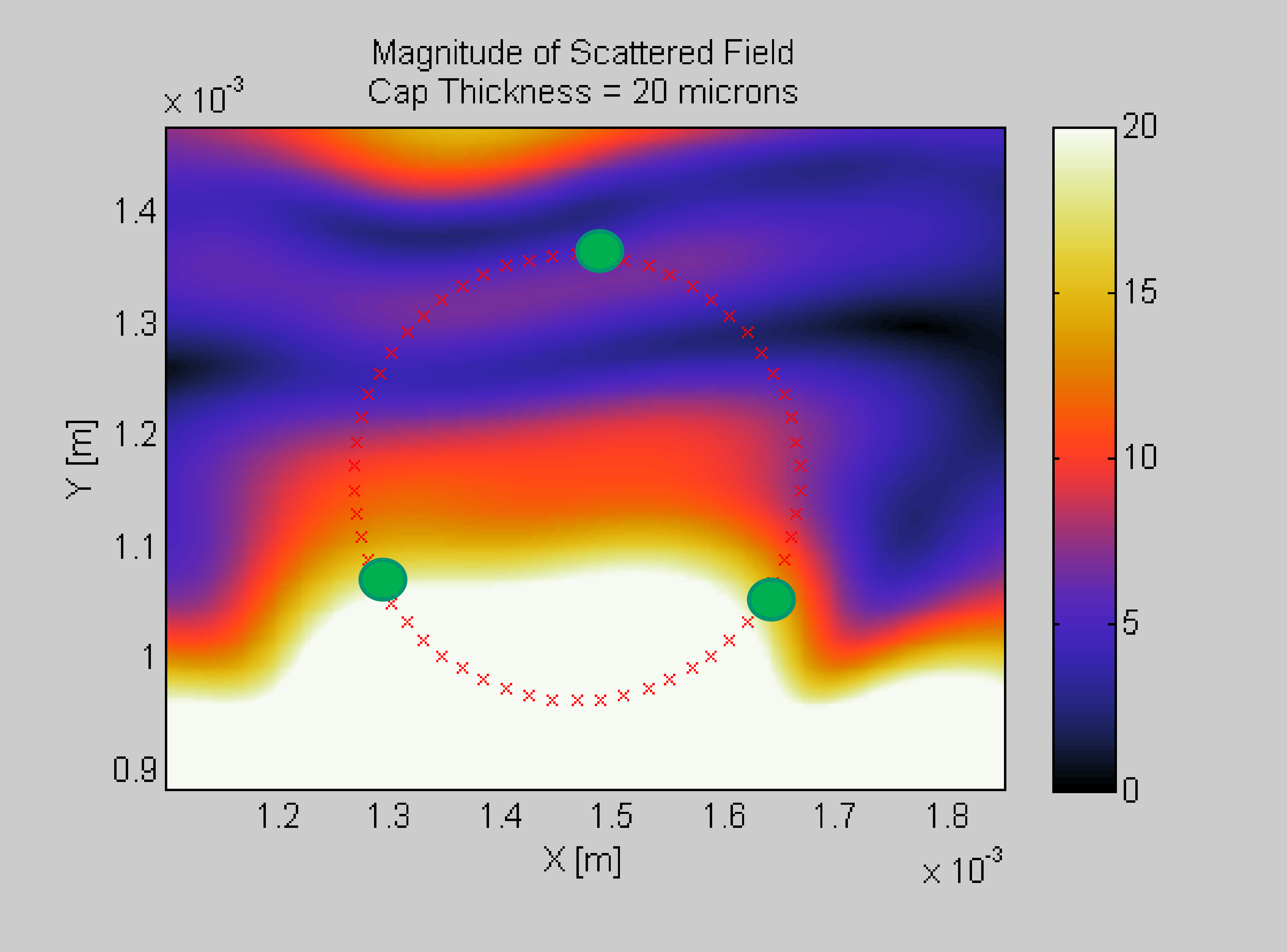
Cap Thickness = 20 microns

Cap Thickness = 65 microns





Circle Method: 60 Measurement Points; 400 GHz



Conclusions: Catheter-Based Terahertz Sensor

Non-destructively identify disease

- Relationship between cap thickness and scattered field magnitude
- Relationship between cap thickness and scattered field slope
- Can determine position of vulnerable plaque

MICROWAVE ABLATION OF ARRHYTHMIAS

Catheter Ablation of Arrhythmias

- Ventricular tachycardia is a major cause of sudden death
- Sudden cardiac death occurs in ~500,000 individuals each year in the U.S. alone
- Arrhythmias depend upon a critical zone of myocardial tissue
- Once this critical zone is found, an arrhythmia may be treated by destroying this region of tissue
- This region may be large with considerable depth

Microwave Ablation of Arrhythmias

- Microwave energy proposed to increase surface area and depth of the ablation region
- Development of the appropriate antenna for each type of lesion is important
- Conventional radiofrequency ablation techniques have had limited success in the treatment of ventricular tachycardia
- Larger lesions with greater depth and surface area are needed

Cardiac Ablation: Problem Addressed

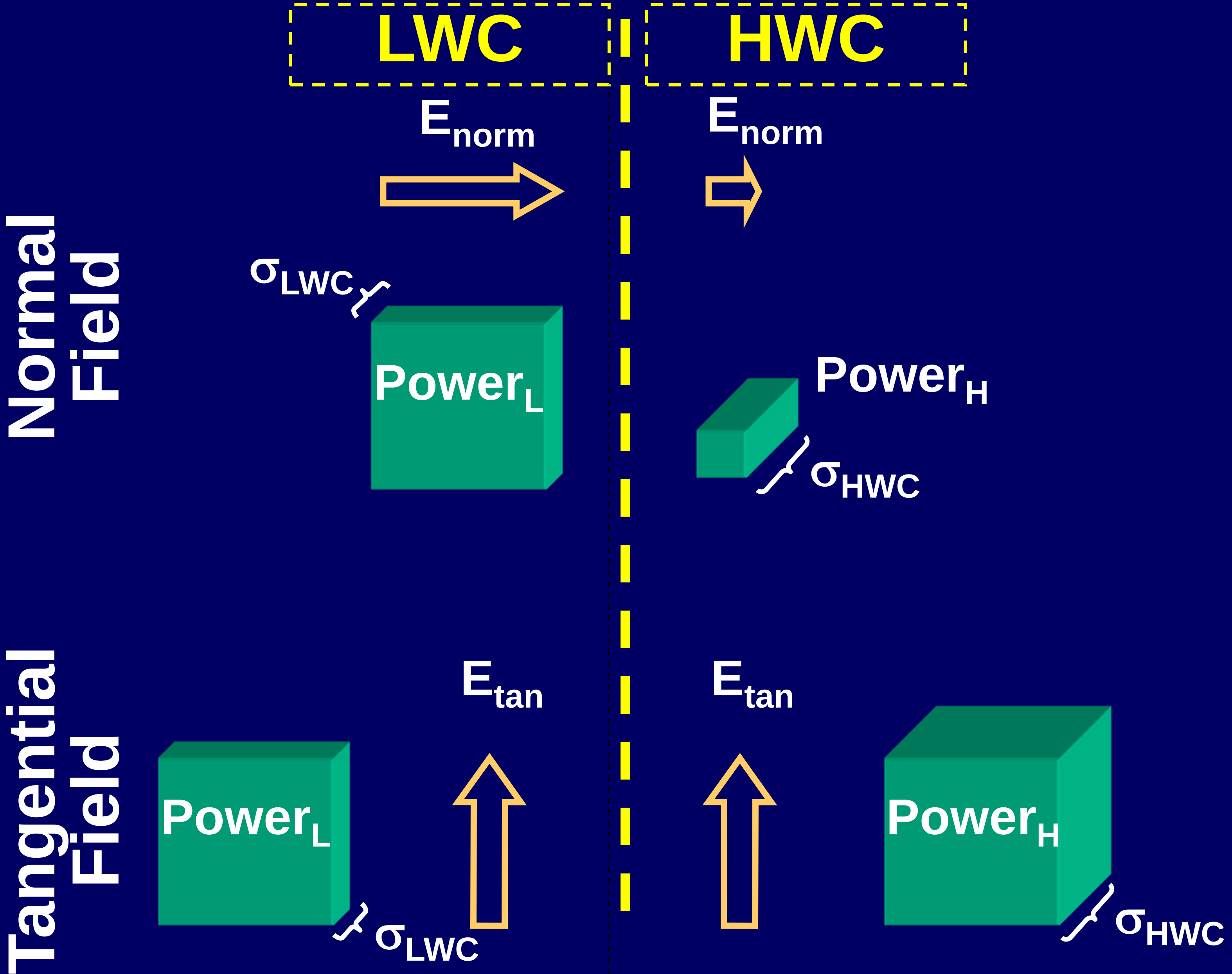
- **Treat abnormal heart rhythms by overheating & ablating cardiac tissue**

- **Technical Approach:**
  Use an internal focused microwave applicator to create a large, deep lesion on the inside wall of the ventricle

- **Novel Antenna Applicator:**
  Develop a deployable, catheter-fed wide-aperture spiral antenna tuned to efficiently couple with cardiac tissue

- **Technical Challenges:**
  1) **Ensure efficient electromagnetic coupling to tissue**
  2) **Maintain axial constructive interference at depth,**
  3) **Prevent surface charring**

Power Deposition Across LWC/HWC Boundary Depends on Incident Field Orientation


LWC
HWC
Normal Field
E_{norm}
E_{norm}
σ_{LWC}
$Power_L$
$Power_H$
σ_{HWC}
Tangential Field
E_{tan}
E_{tan}
$Power_L$
σ_{LWC}
$Power_H$
σ_{HWC}

Spiral Antenna Design Principles

1) Constructive interference from a wide aperture allows for focusing at depth and more uniform heating.

2) Spiral or loop wire antenna can be formed after distal end of catheter is placed in ventricle, and later retracted after heating is completed.

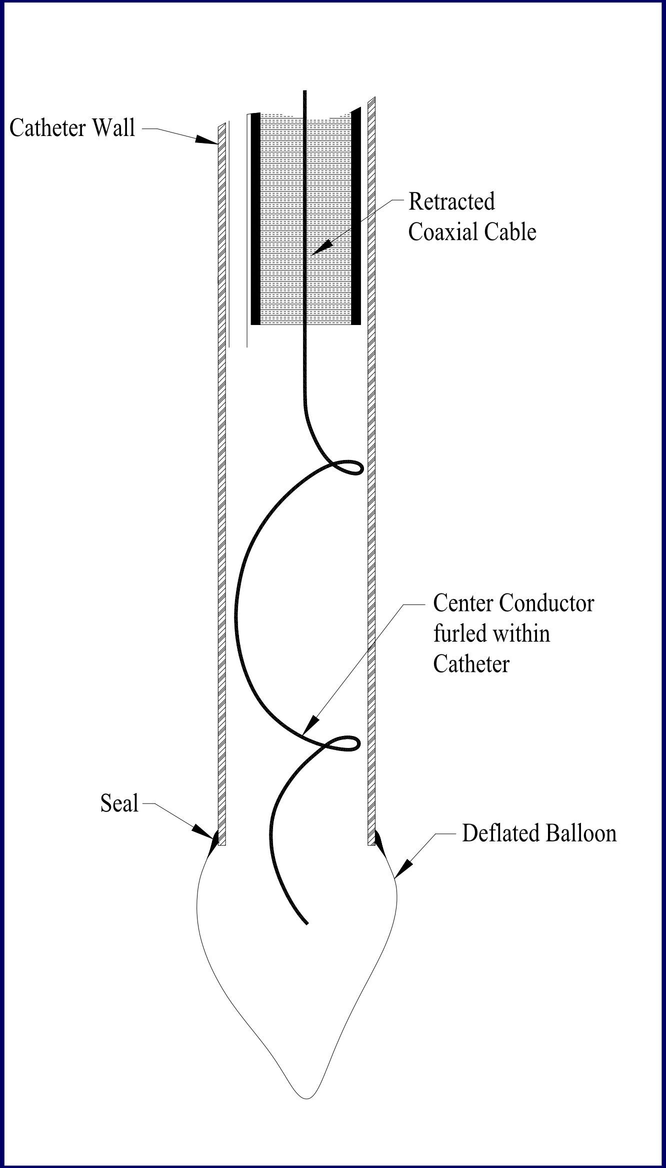
3) For a 1 wavelength circumference loop, EM phase differences cancel current direction differences for maximizing field on axis.

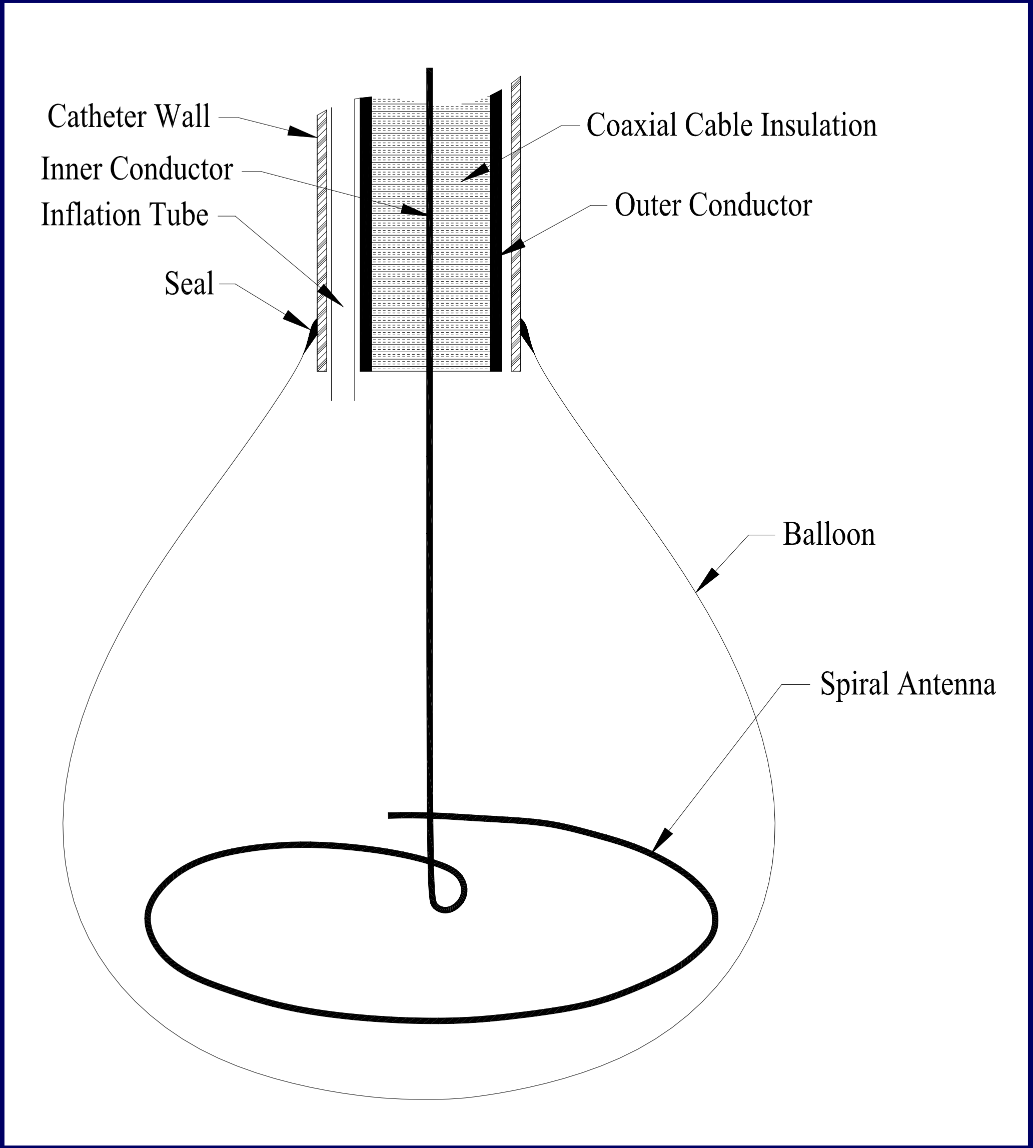
4) Power density falls off exponentially, but not as fast as RF (r^{-4})

5) Surrounding the spiral with low electrical conductivity fluid (oil, RTV, air, etc.) prevent current flow directly into tissue, and concentrates power in the forward direction.

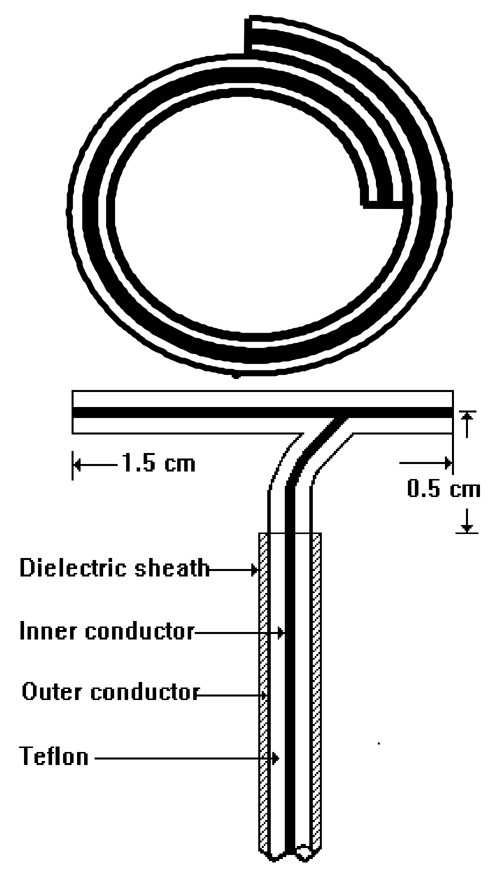
$1/r^4$

Furled and Unfurled Catheter –Based Spiral Antenna


Catheter Wall
Retracted Coaxial Cable
Center Conductor furled within Catheter
Seal
Deflated Balloon


Catheter Wall
Inner Conductor
Inflation Tube
Seal
Coaxial Cable Insulation
Outer Conductor
Balloon
Spiral Antenna

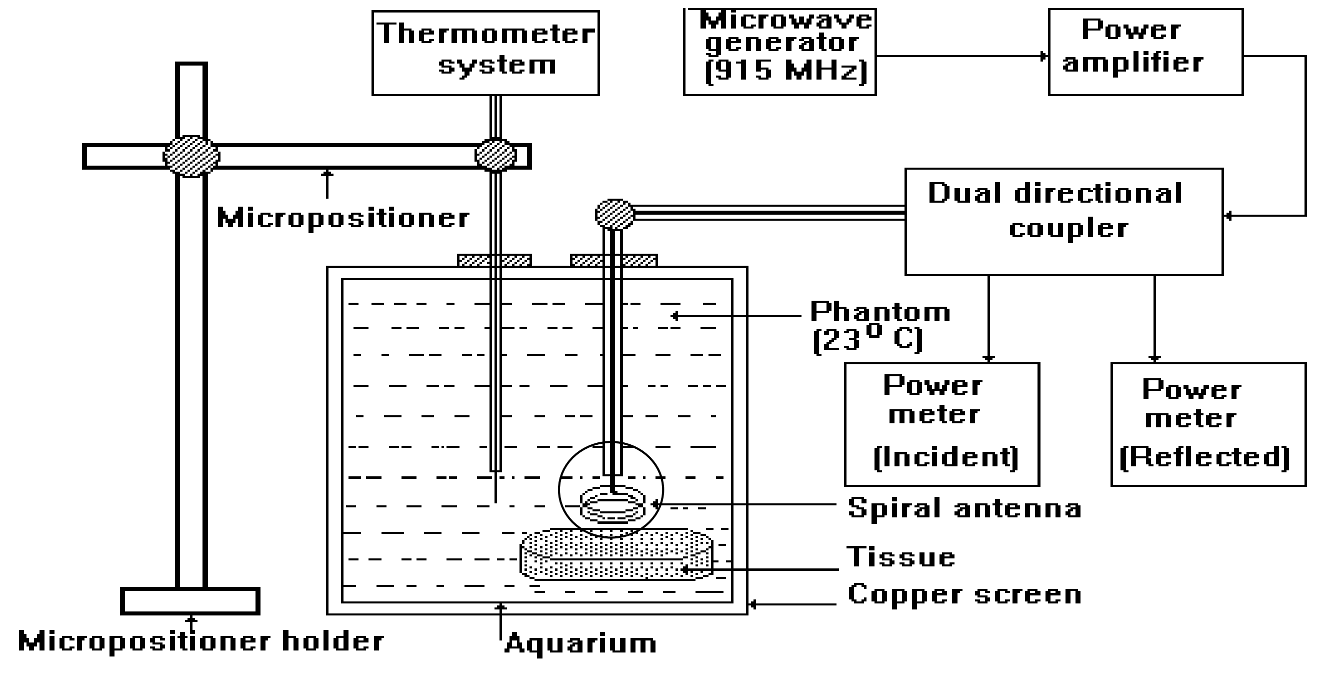
Unfurled Spiral Antenna Geometry


1.5 cm
0.5 cm
Dielectric sheath
Inner conductor
Outer conductor
Teflon

Wavelength at 915 MHz in HWC tissue: 4.6cm.

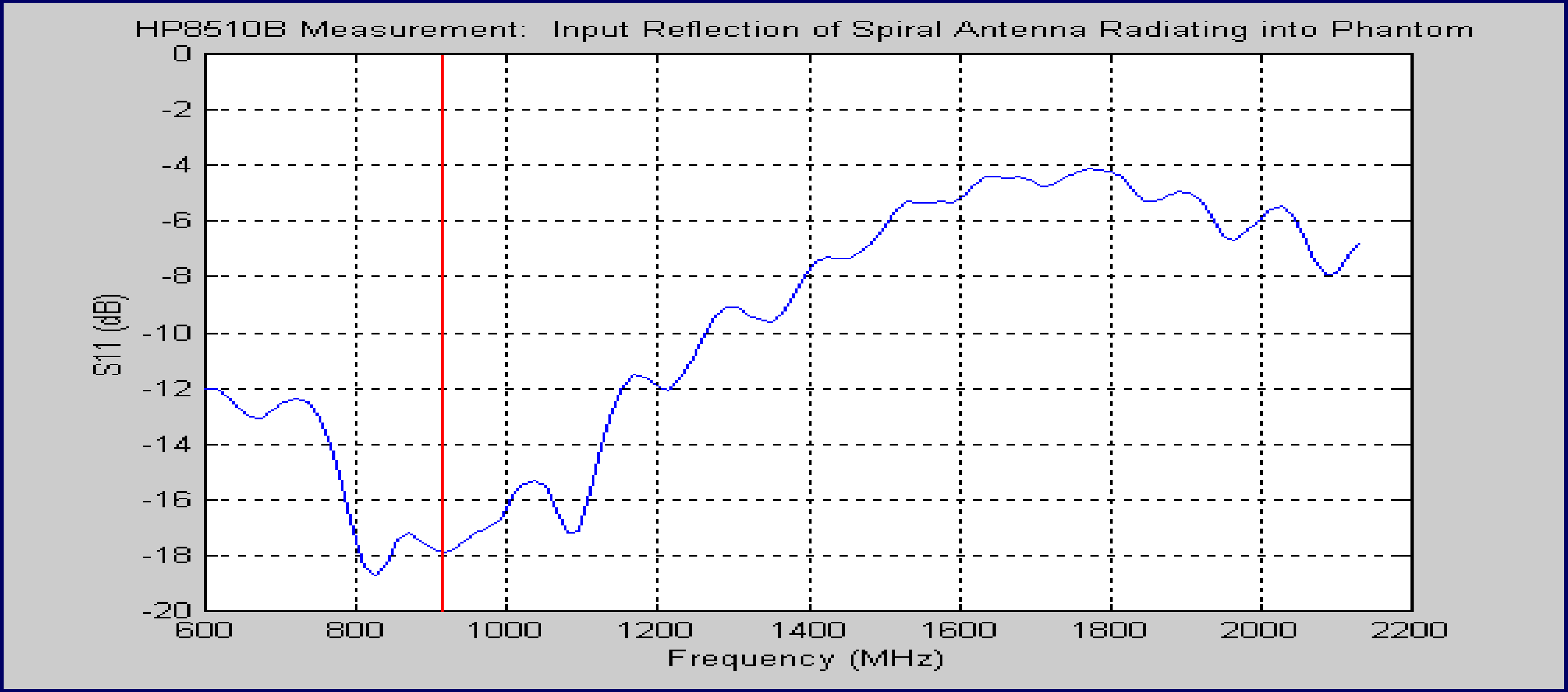
Teflon completely insulates center conductor.

Schematic Representation of *In Vitro* Experimental Setup


Thermometer system
Microwave generator (915 MHz)
Power amplifier
Micropositioner
Dual directional coupler
Phantom (23 ⁰ C)
Power meter (Incident)
Power meter (Reflected)
Spiral antenna
Tissue
Copper screen
Micropositioner holder
Aquarium

- Copper screen enclosure surrounding aquarium tank
- Cardiac muscle tissue phantom
- Spiral antenna inside balloon

Spiral Antenna Coupling to Biological Tissue

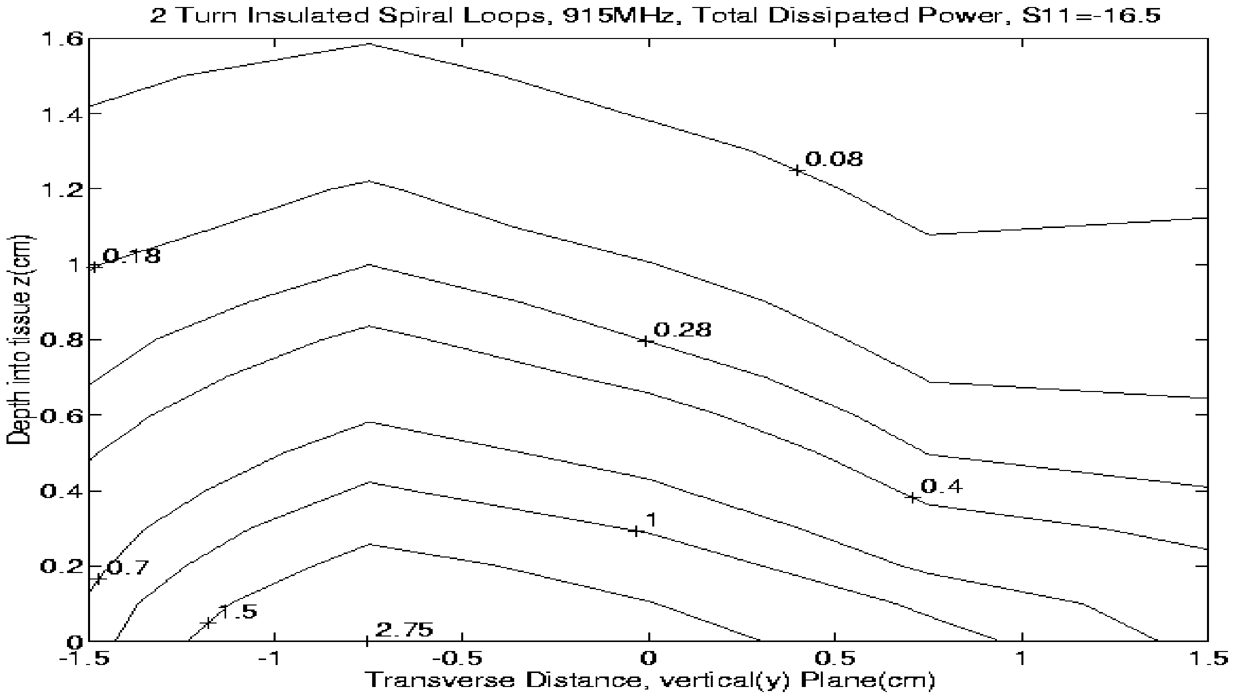


Measured reflection coefficient of spiral inside silicone oil filled balloon, radiating into cardiac tissue phantom medium.

At 915MHz, < 2% power supplied returns to the source: more than 98% enters and heats the medium.

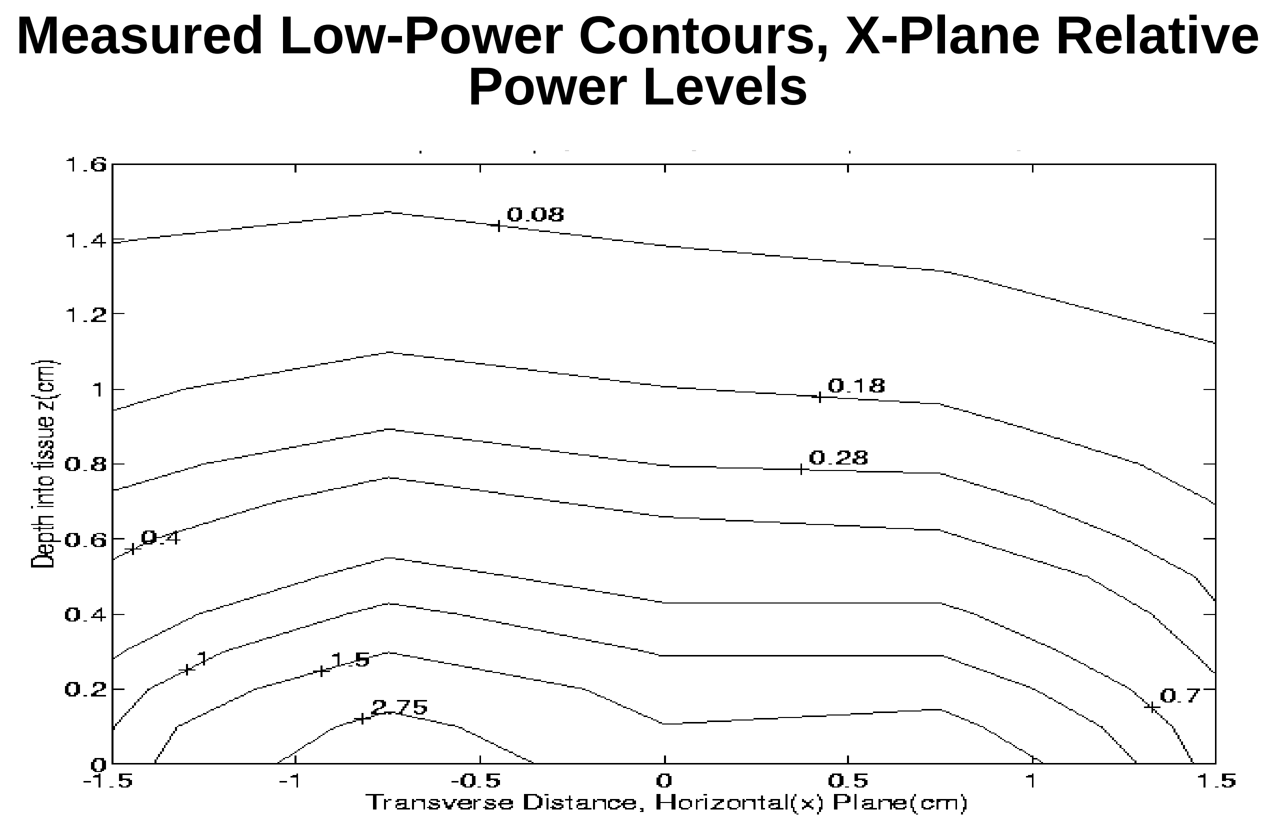
Measured Low-Power Contours, y-Plane

Relative Power Levels



- Network analyzer with small coaxial probe measurements
- Power deposited by the spiral in tissue-equivalent phantom
- Antenna at bottom with feed point y = - 0.75cm
- Maximum power at 1cm depth is 1/10th surface power

Thermal Response of Cardiac Tissue as a Function of Position

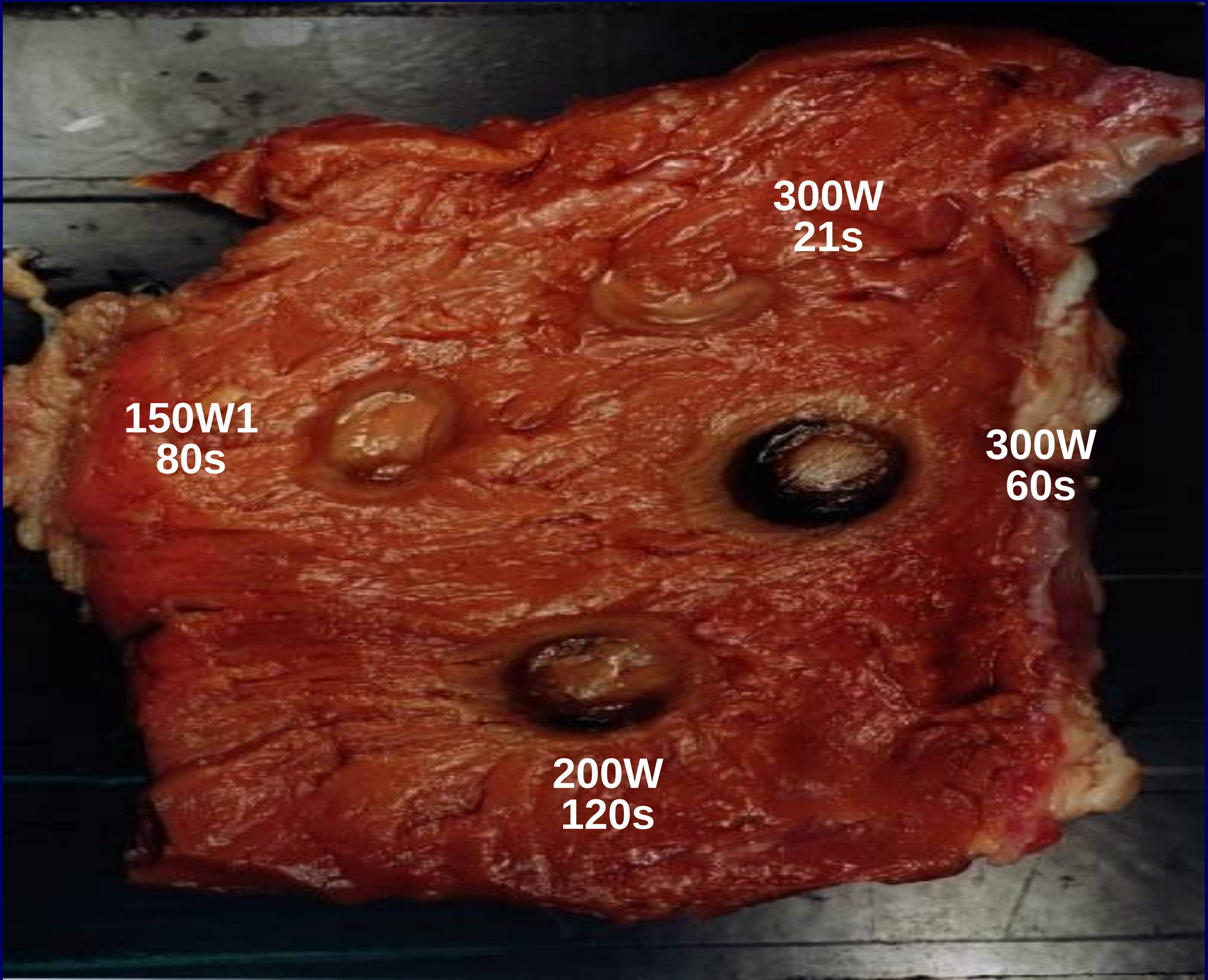


Two sides of the spiral loop result in power maxima at x = +/- 0.75cm.

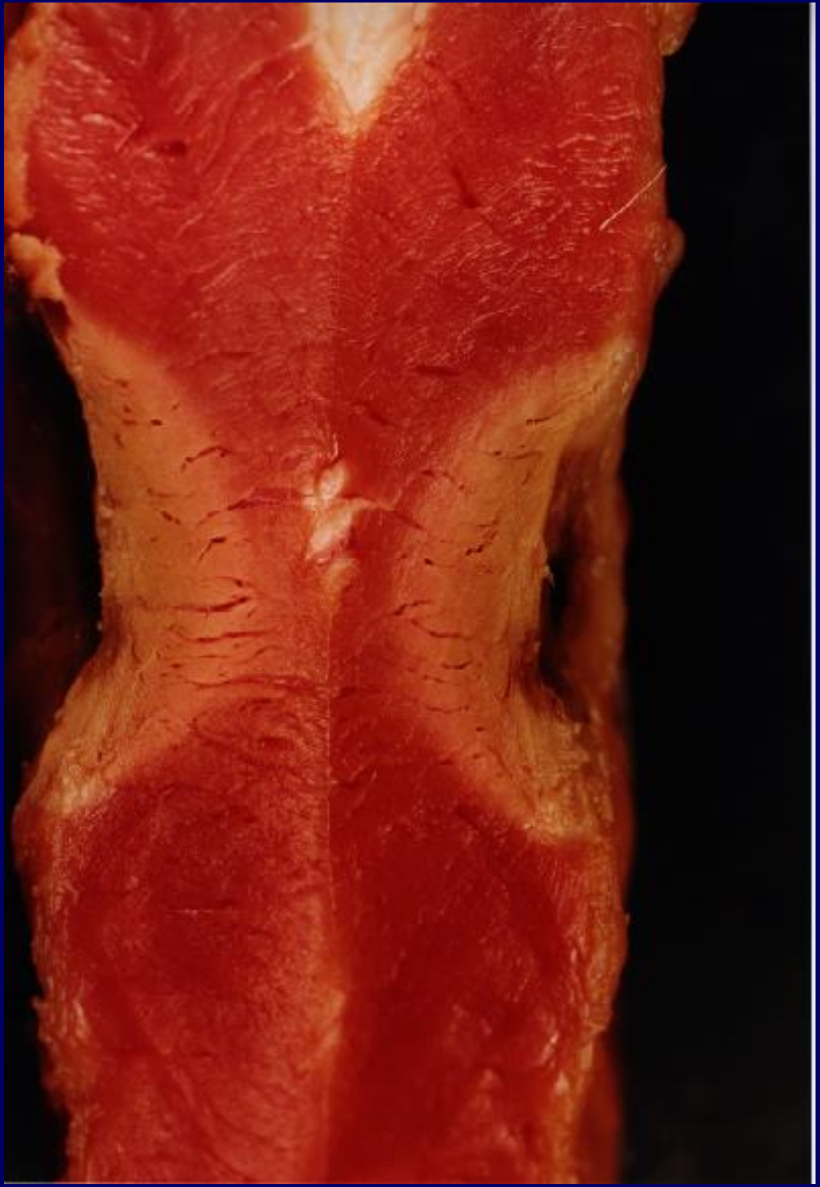
Microwave Ablation Experimental Results

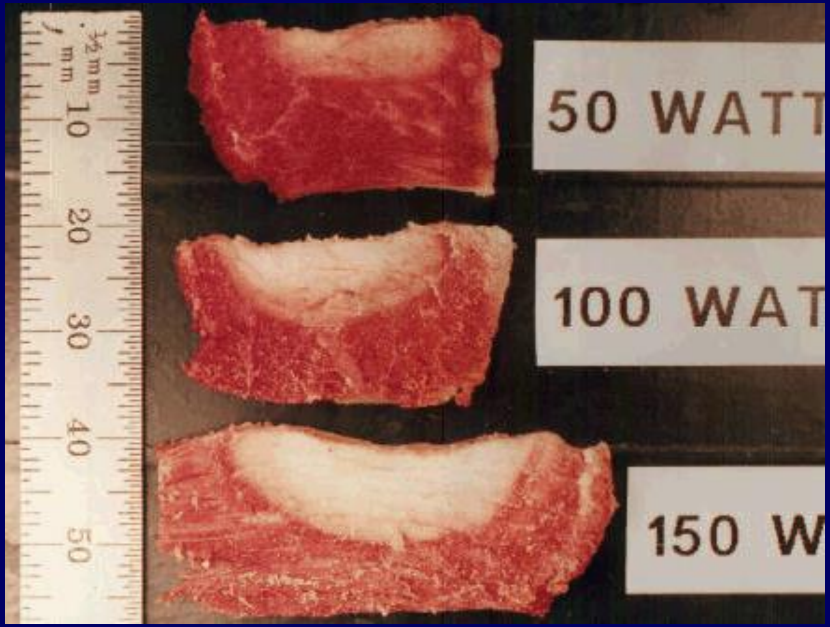
- *In vitro* porcine heart tissue
- Power 150W to 300W
- Heating times 30s – 3 min.
- Silicone oil best heating characteristics, *in vivo* experiments must use a more physiologically benign fluid. Possibility: perfluorocarbon blood substitute.
- Lesions created by spiral applicator (white/gray areas)
    - Circular, 1.5 to 2.0cm diameter
    - Depth 0.2 - 0.7cm into the cardiac tissue.
- Excessive energy (Power * Time) leads to charring, with lesion diameter > antenna diameter.
- For 300W for 42s, or 200W for 120s, heating pattern is uniformly hemispherical.

Silicone Oil Filled Balloon Test Lesions

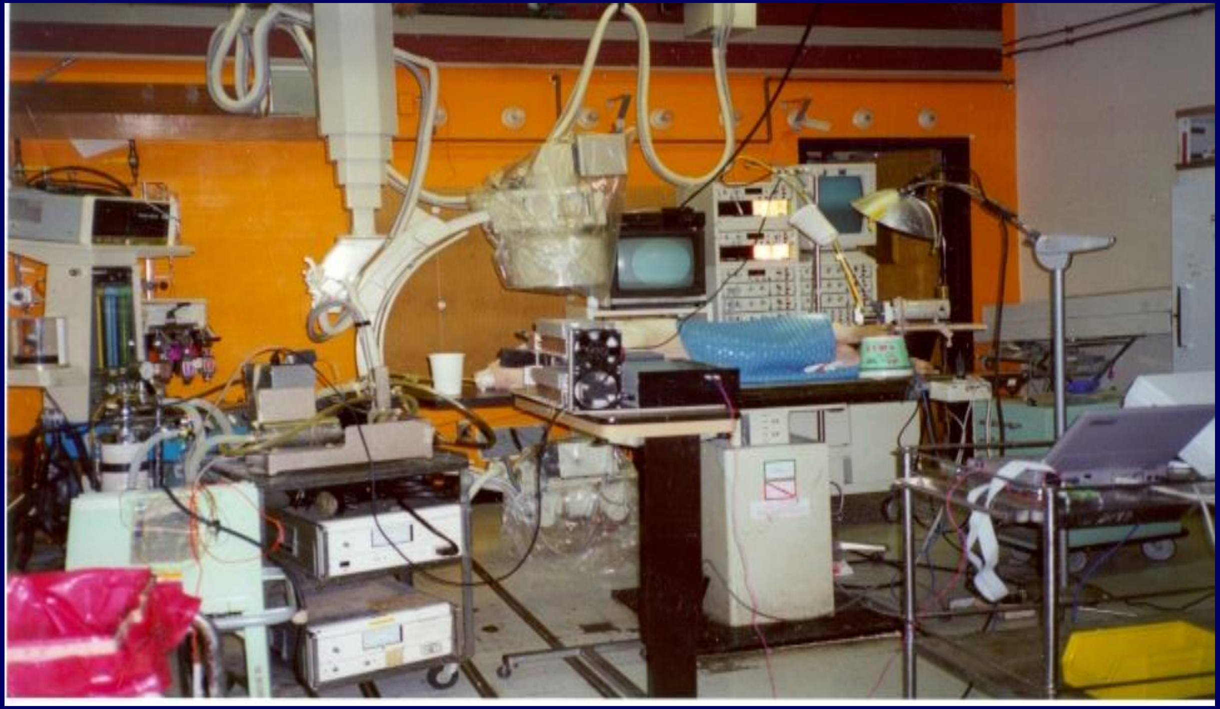

300W
21s
150W1
80s
300W
60s
200W
120s

200W 120s Lesion, Primary Cross Section



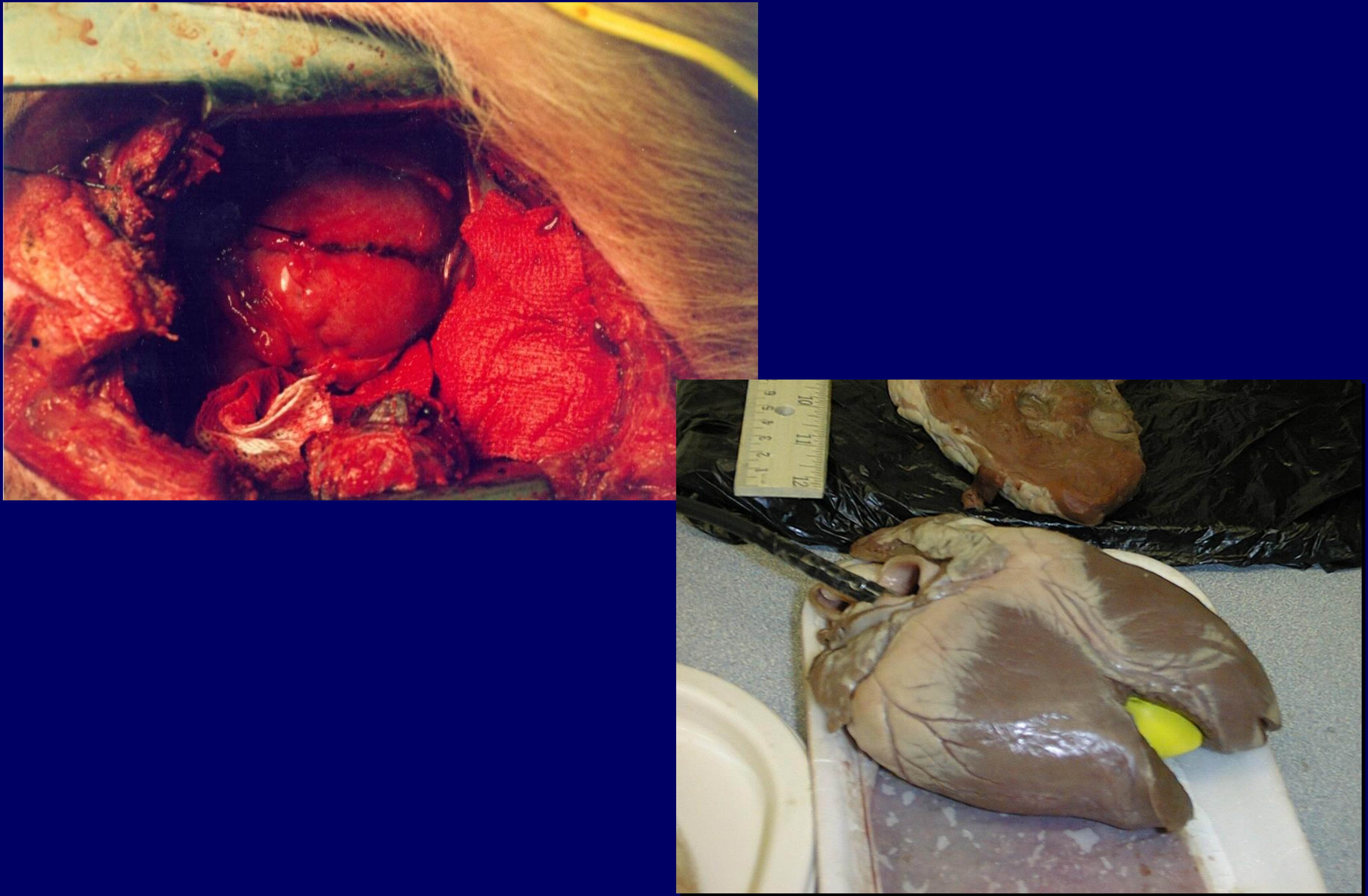

½ mm
mm
10
20
30
40
50
50 WATT
100 WAT
150 W

In Vivo Experimental Test Facility: Operating Room at NEMC



- **Operating table, anesthesia delivery system, EKG**
- **Fluoroscopic camera**
- **Microwave power source**
- **Fiber-optic temperature monitor**

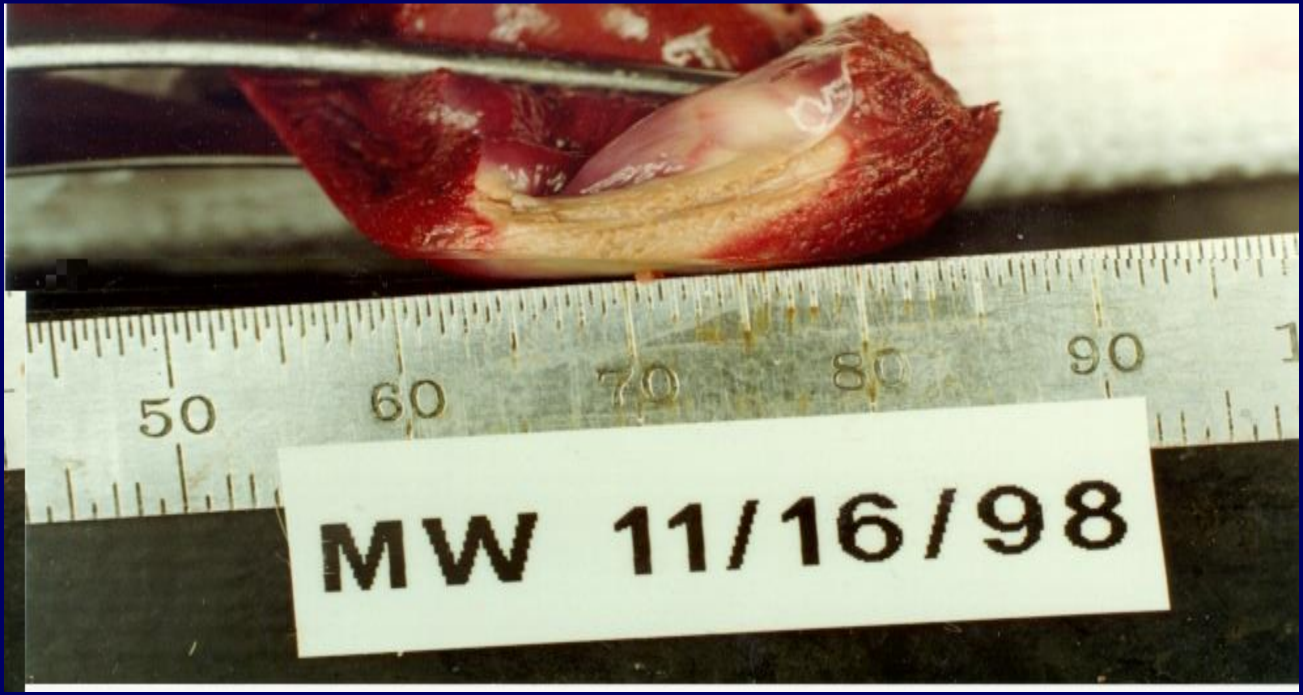
Exposed *In Vivo* Pig Heart, Prior to Ablation



Cardiac Ablation *In Vivo* Experimental Results

- *In vivo* experiments on anesthetized pigs
- Deflated antenna applicator inserted through a small hole cut through the left atrial wall
- Balloon inflated with air, antenna pressed against the inner wall of the left ventricle
- Power applied 60 - 180 s, 50 - 150W
- Pig tolerated multiple applications of heat leading to multiple lesions, then was sacrificed
- Heart tissue was removed, heating damage and lesion size
- All lesions were circular, diameters: 1.5 to 2.0cm, depth: 0.8cm into the cardiac tissue, no charring
- Some lesions were transmural, extending throughout entire thickness of heart wall. Transmural lesions are unlikely when applying RF ablation.

Ablation at Left Ventricle Apex, Showing Transmural Ablation


50
60
70
80
90
MW 11/16/98

- *In vivo* microwave ablation.
- 150 W 915 MHz microwave power applied for 60 s.
- Direct contact of antenna to heart wall.

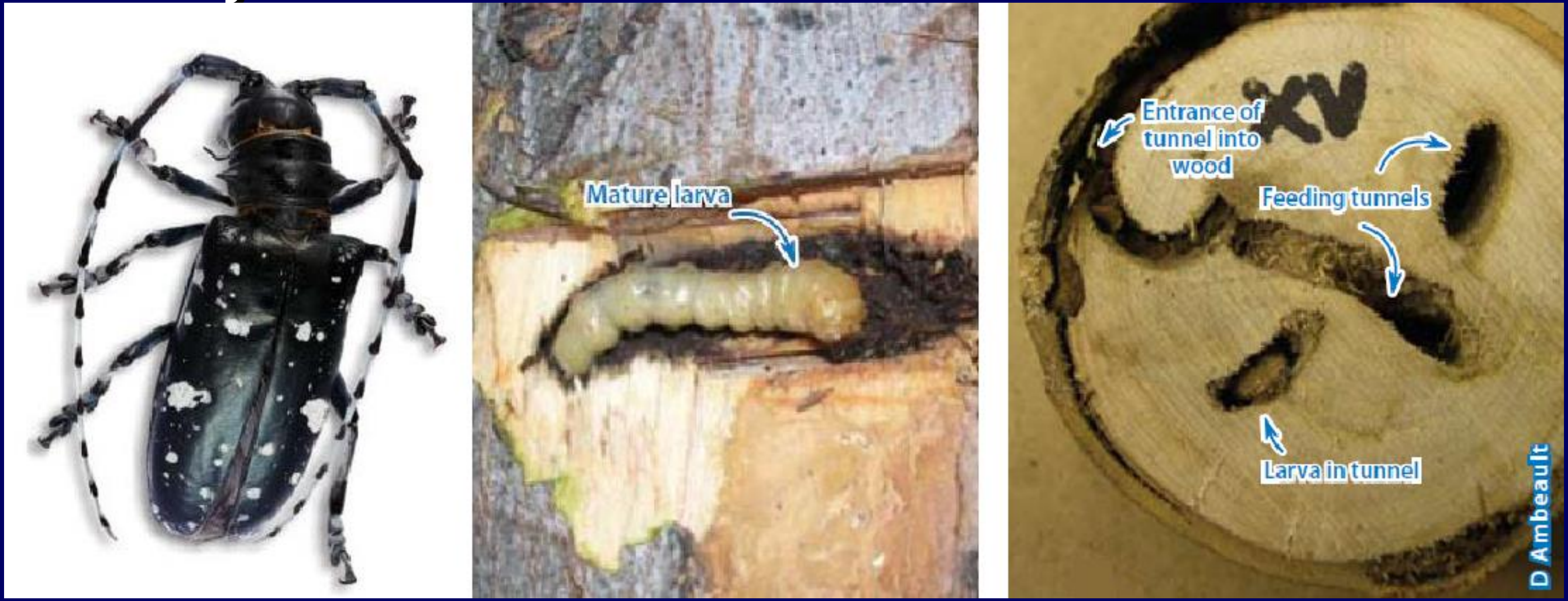
Ablation Conclusions

- A deployable spiral can act as a wide aperture antenna to focus power deeply into cardiac tissue.
- With the proper spiral diameter and wire length, both focusing and efficient microwave coupling to tissue is possible: at 915MHz (ISM band) , a 1.5cm diameter spiral with 1.25 turns radiates 98% of the power.
- Surrounding the spiral with a balloon filled with a non-conducting fluid directs heat forward into tissue, and prevents direct antenna contact charring.
- High power tests on *in vitro* and *in vivo* cardiac tissue indicate flexible and controllable heating patterns with hemispherical contours, in agreement with both modeled and measured low power electric field patterns.

MICROWAVE RADAR DETECTION OF TREE INVESTATION

The Asian Longhorned Beetle Infestation in Maple Trees

- **Beetles leave little visible evidence of infestation until it is too late.**
- **Larvae eat away the inside of the tree, effectively killing it.**
- **Current response to infestation results in the loss of hundreds of maple trees.**
- **In the Northeast, maple syrup production is a $65 million industry.**


Mature larva
Entrance of tunnel into wood
XV
Feeding tunnels
Larva in tunnel
D Ambeault

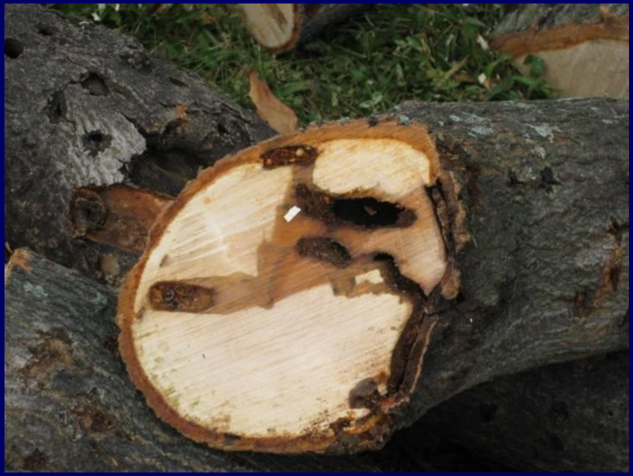
Ric, Jozef et al., "Detecting Signs and Symptons of Asian Longhorned Beetle Injury: Training Guide", Her Majesty in Rights of Canada, Canada, 2006.

Microwave Sensing as a Solution

- Microwaves are safe and would not further damage the trees in question.
- The air that fills the voids is materially different than the surrounding wood.
- The cost of losing areas of maple trees far exceeds the cost of radar systems.

Courtesy of the ALB Facebook

Courtesy of Jennifer Forman Orth

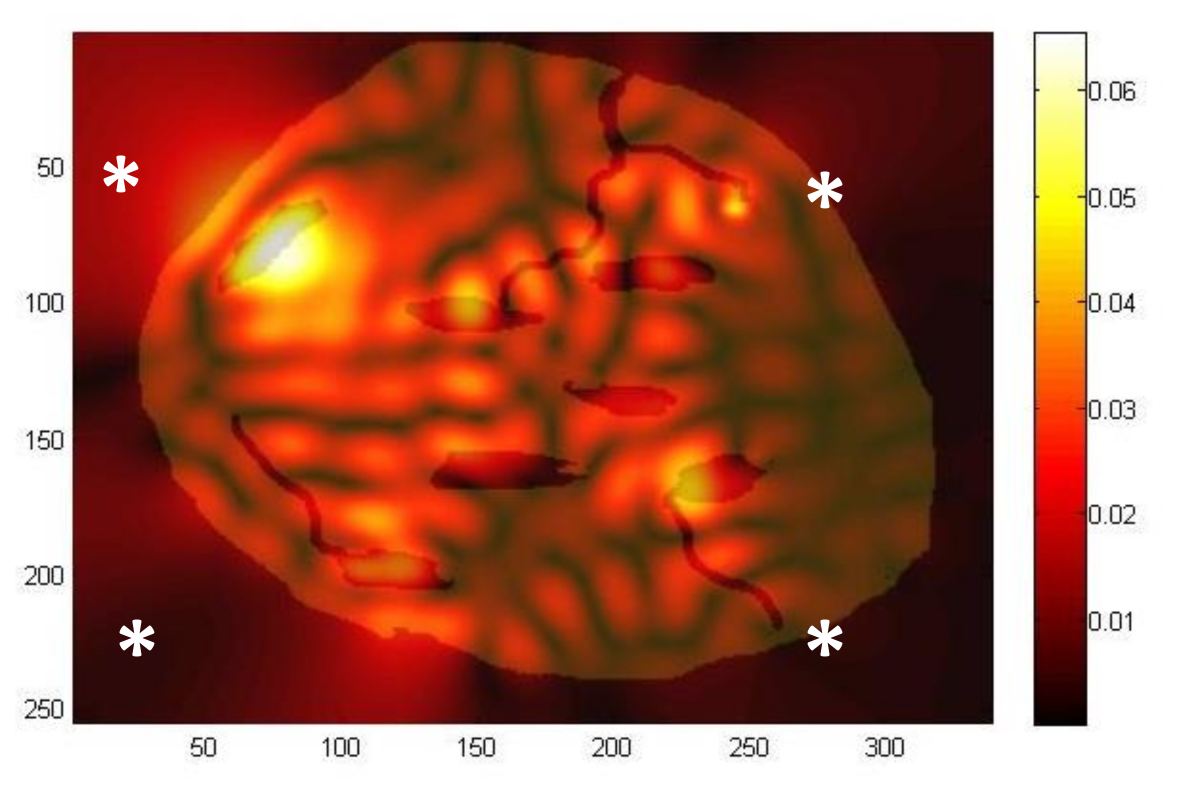


Courtesy of Douglass, USDA APHIS-PPQ

FDFD Computational Model

Can we detect void-related response outside the tree?

FDFD shows difference between a cross section with and without voids

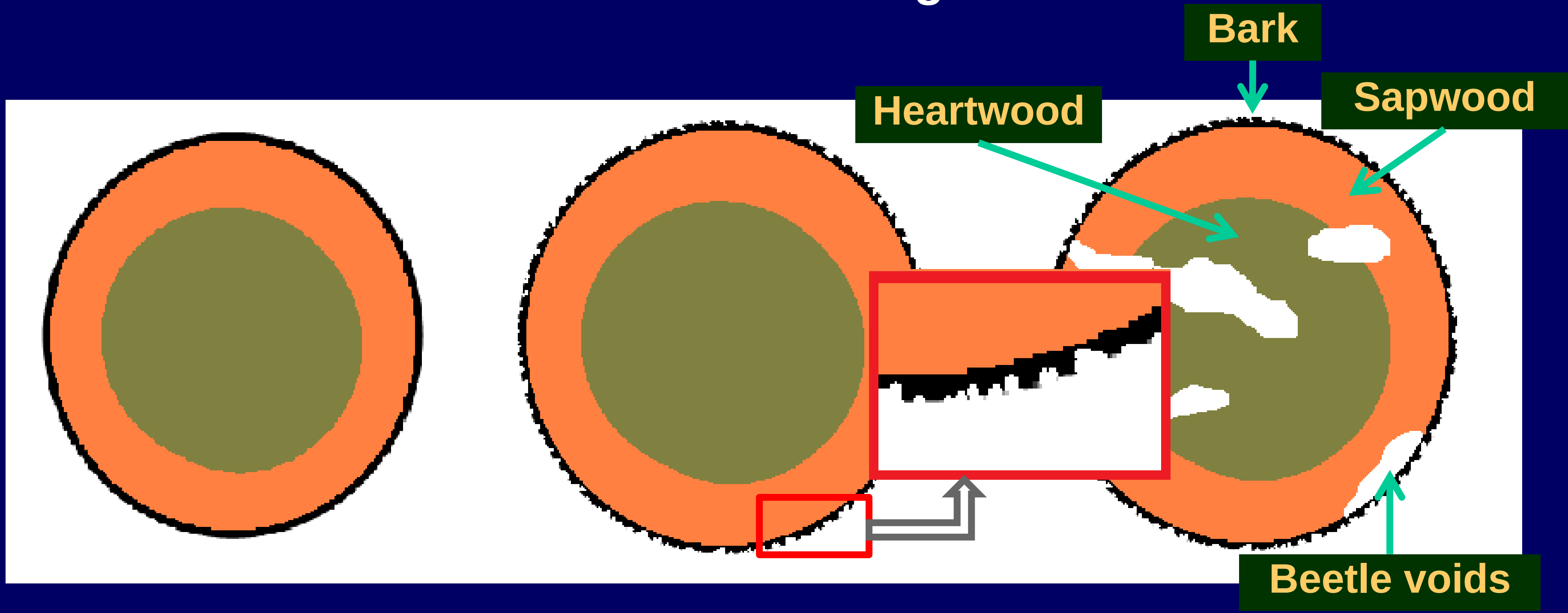


*Asterisks represent point source locations

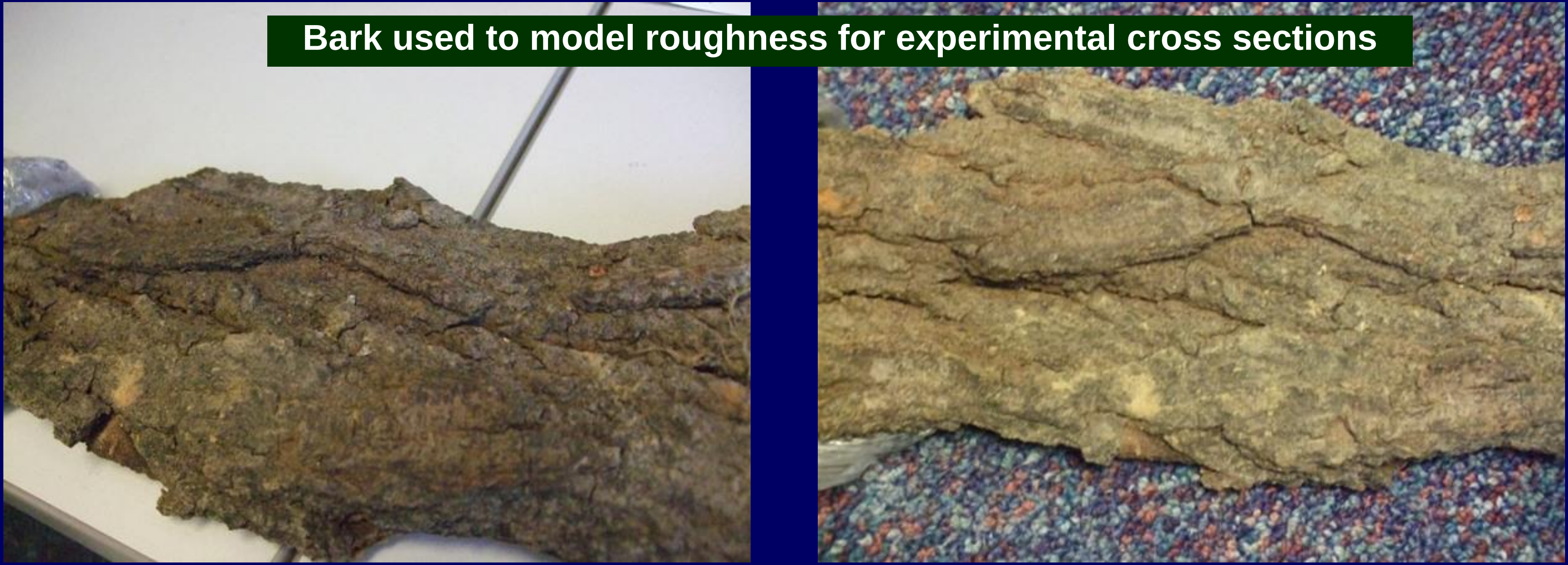
Computational Experimental Geometry

	Bark	Sapwood	Heartwood
Dielectric Constant	7.3	13.45	11.8
Loss Tangent	0.16	0.18	0.19

Several sample tree cross sections were created: healthy with smooth bark, healthy with rough bark, and infested with rough bark.


Bark
Heartwood
Sapwood
Beetle voids

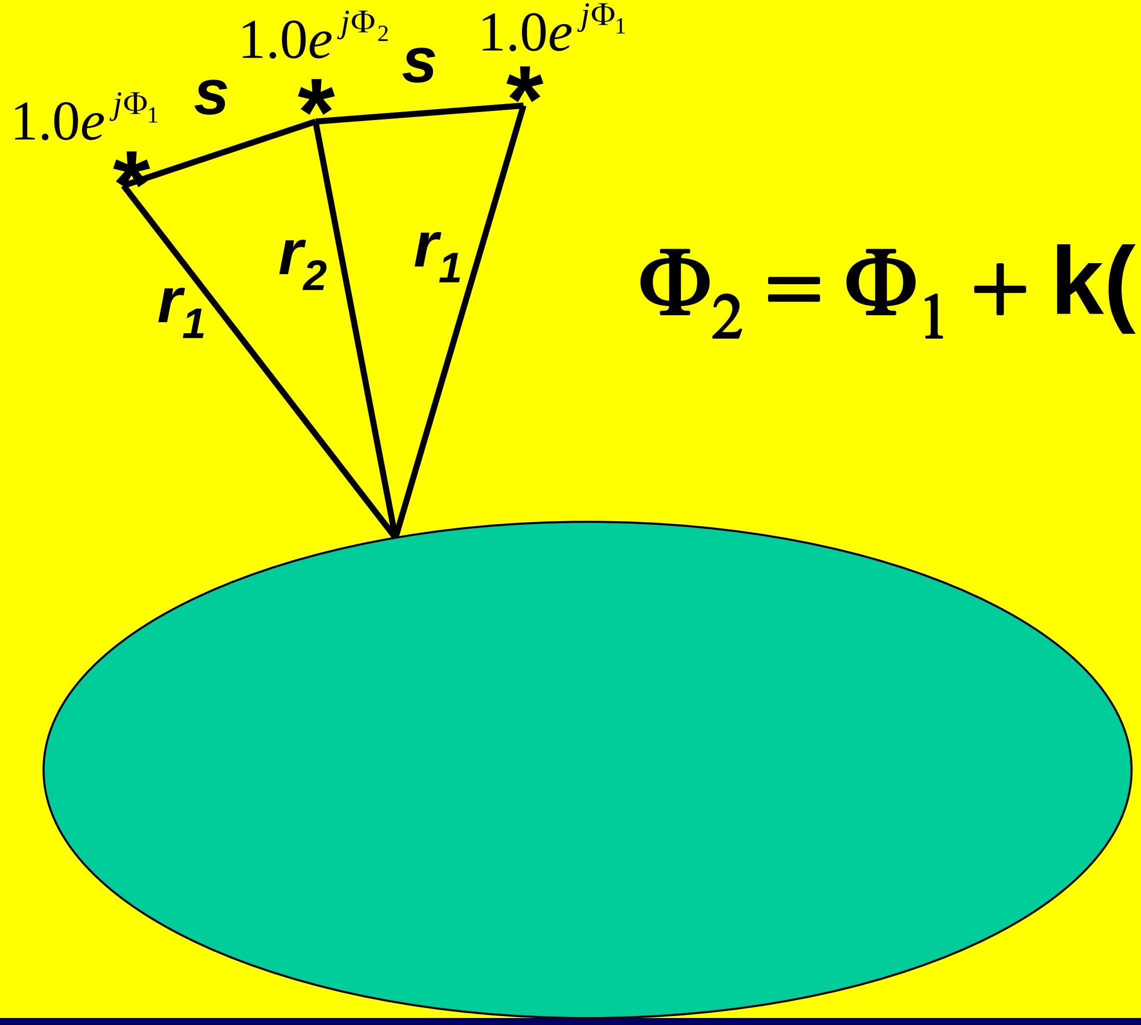
Accounting for Bark Roughness



Bark used to model roughness for experimental cross sections

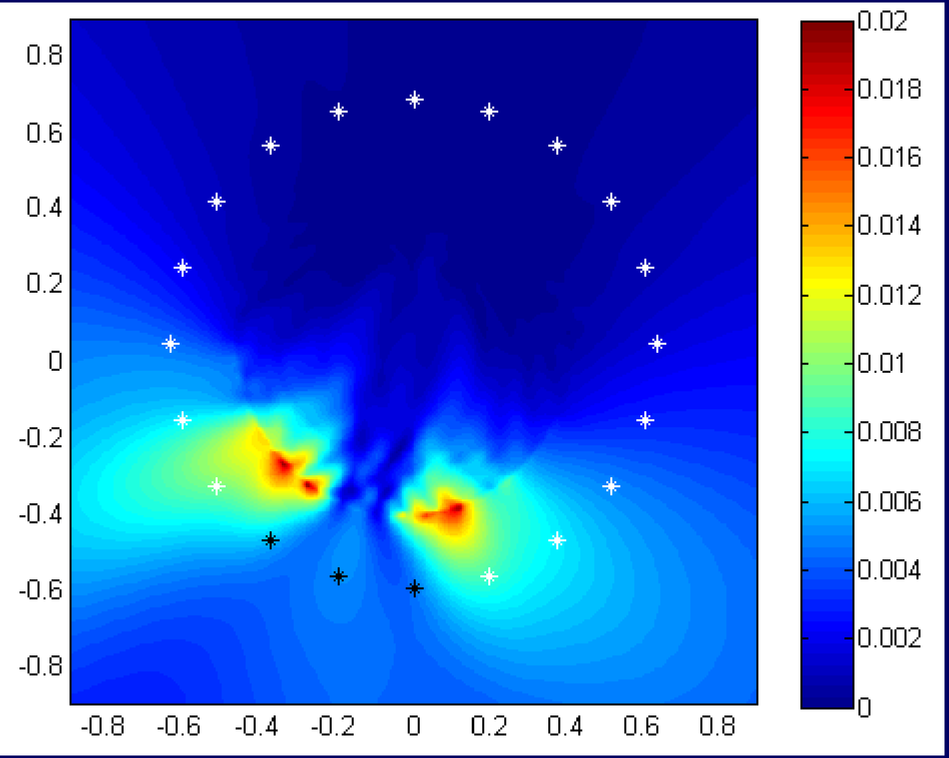
- Bark is randomly rough
- It is impractical to account for this rough surface response
- By taking the difference between tree with smooth bark and with rough bark scattered fields, we determined a threshold for the results that filters out bark clutter response.

Adjusting the Phase of the Center Source for Destructive Interference

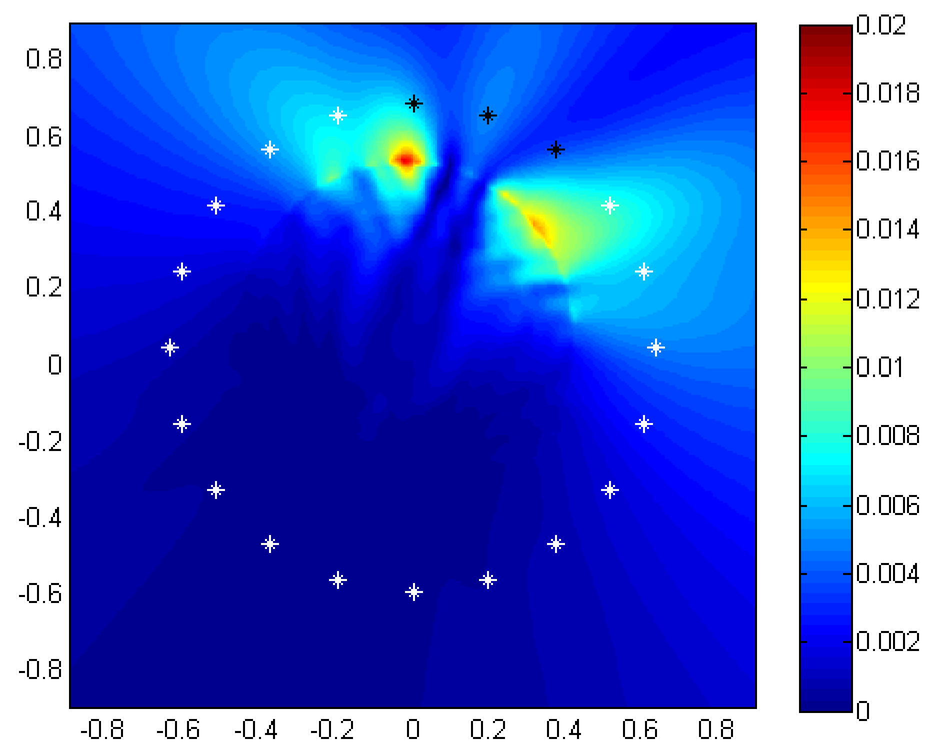

$1.0e^{j\Phi_1}$
s
$1.0e^{j\Phi_2}$
s
$1.0e^{j\Phi_1}$
r_1
r_2
r_1

$$\Phi_2 = \Phi_1 + \mathbf{k}(\mathbf{r}_2 - \mathbf{r}_1) + \pi$$

Bark Clutter Minimization



- Max bark response 0.02
- Scattered field for cross sectional position (in meters)

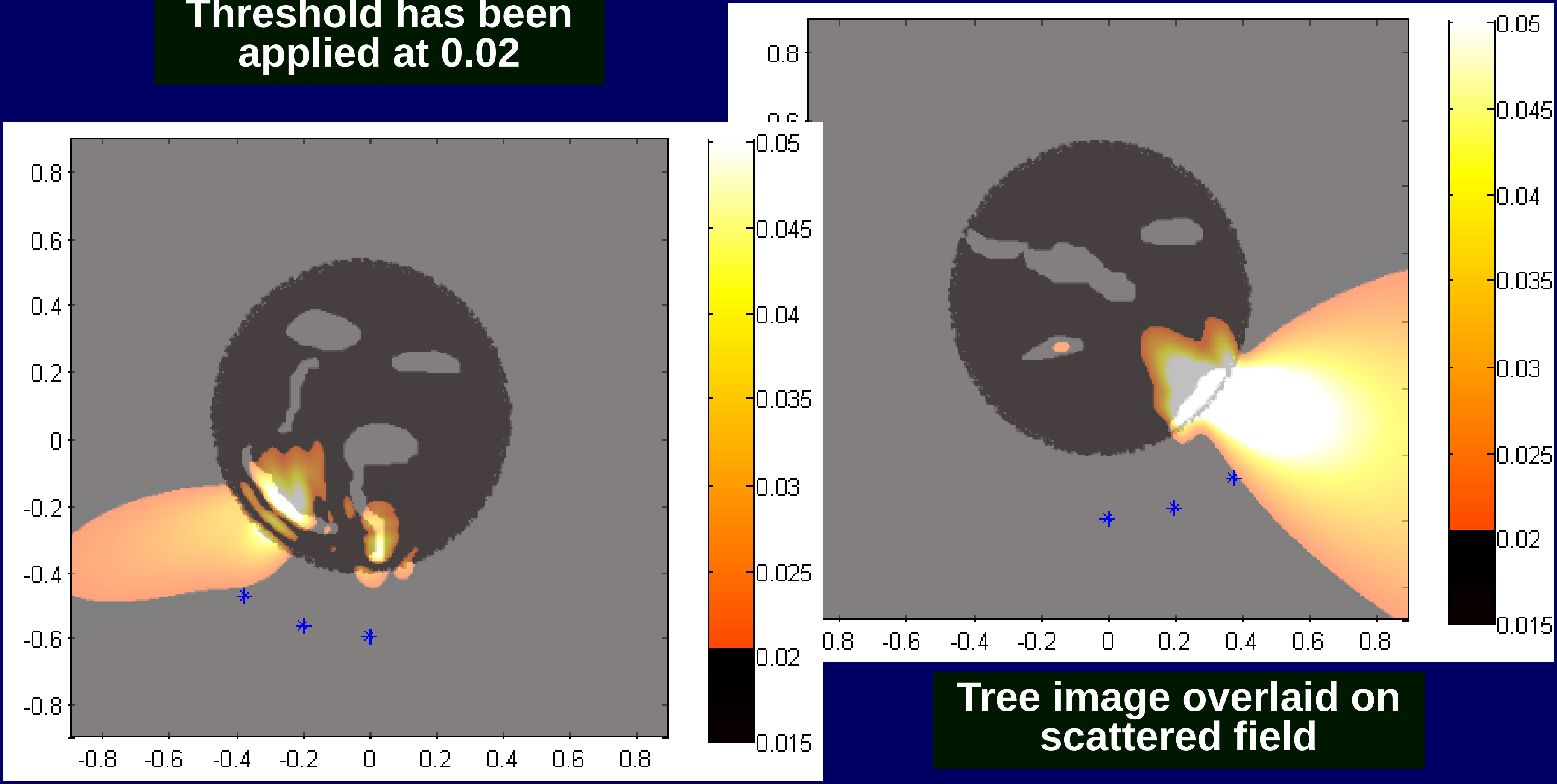


Black asterisks represent transmitting point sources

White asterisks represent inactive ones

Difference Between Healthy and Infested Cross Sections

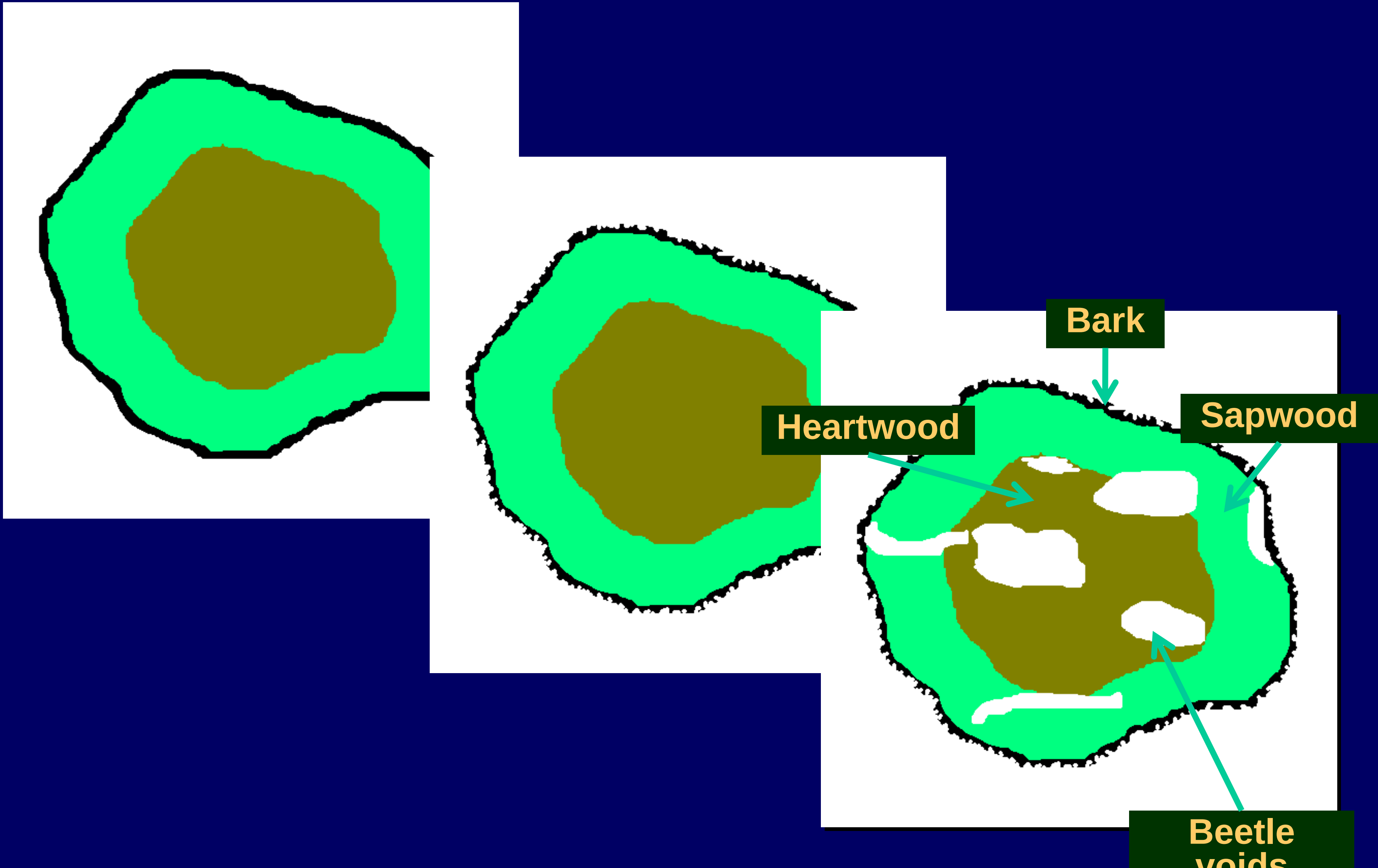
- Voids near the surface generated a significant response in all cases.



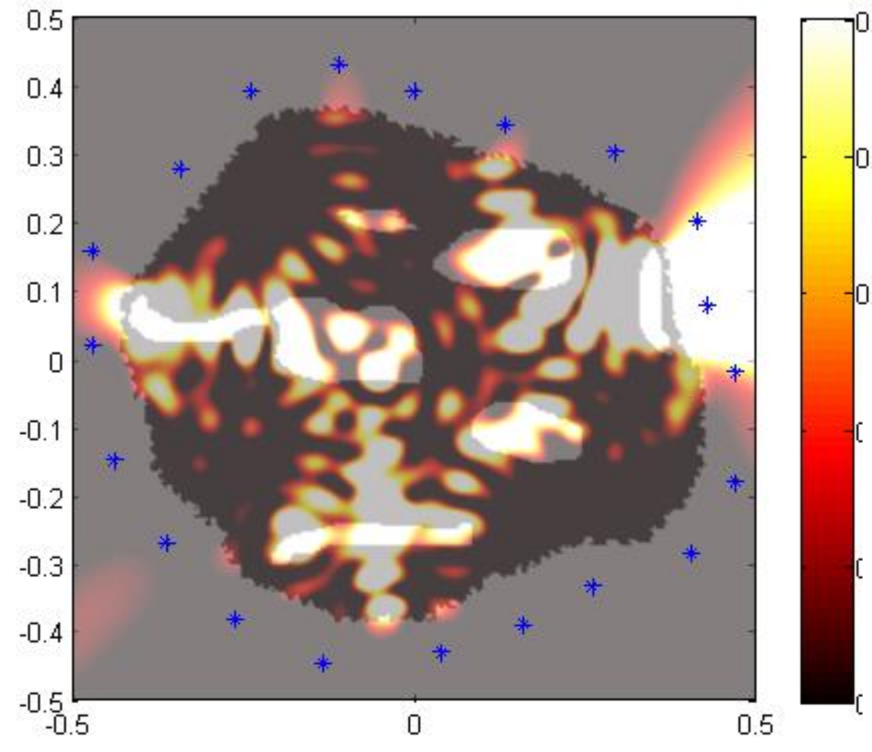
Threshold has been applied at 0.02

Tree image overlaid on scattered field

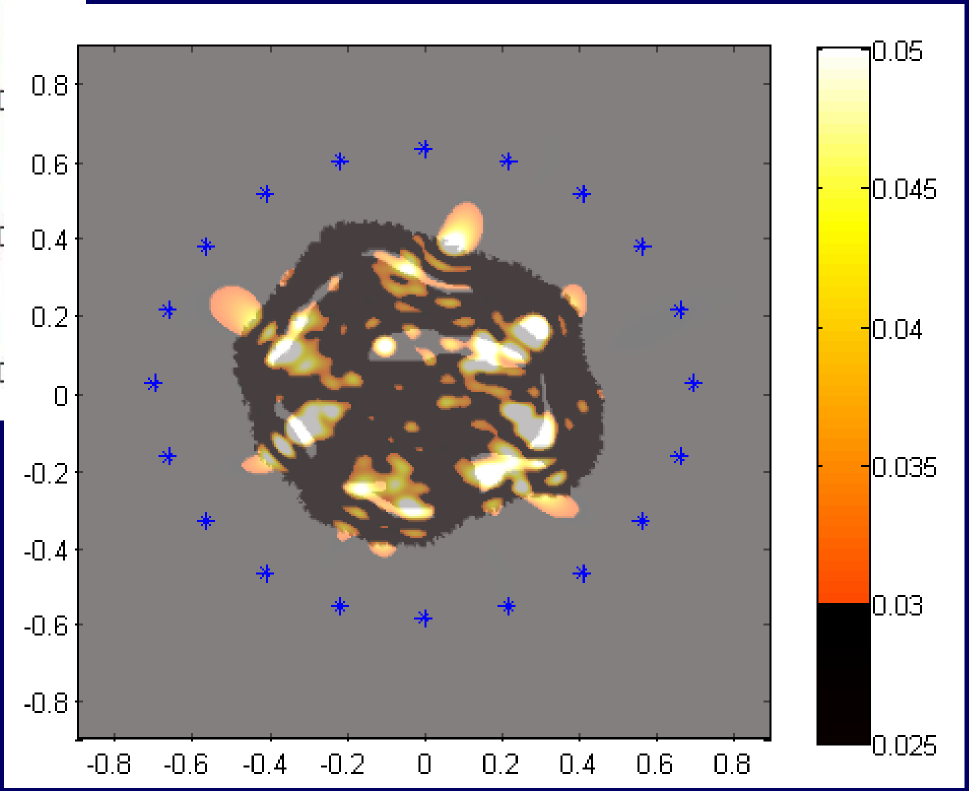
Irregular Geometry


Bark
Heartwood
Sapwood
Beetle voids

Difference Between the Scattered Fields: Healthy vs. Infested



As with the circular geometry, voids close to the surface generate a strong response.



Voids parallel to the bark surface can still be detected even though they may be relatively deep.

Conclusions

- It is possible to detect air voids caused by pest damage in maple trees.
  - It is not necessary to reconstruct the damage pattern, just unambiguously sense its effect.
- Voids closer to the surface consistently produced a stronger response.
  - Because Asian Longhorned Beetle larvae eat the wood closest to the surface first, it is possible to detect infestations early.
- Voids as deep as 20 cm could be detected as long as they were parallel to the bark surface and relatively narrow.
  - True for both regular and irregular geometries.

Overall Summary

- Microwave is a very applicable modality for sensing and treatment
- Penetration, focusing are big advantages -- sensing
- Dissipated power allows for focused heating -- treatment